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(54) **FEEDBACK ADAPTIVE NOISE CANCELLATION (ANC) CONTROLLER AND METHOD HAVING A FEEDBACK RESPONSE PARTIALLY PROVIDED BY A FIXED-RESPONSE FILTER**

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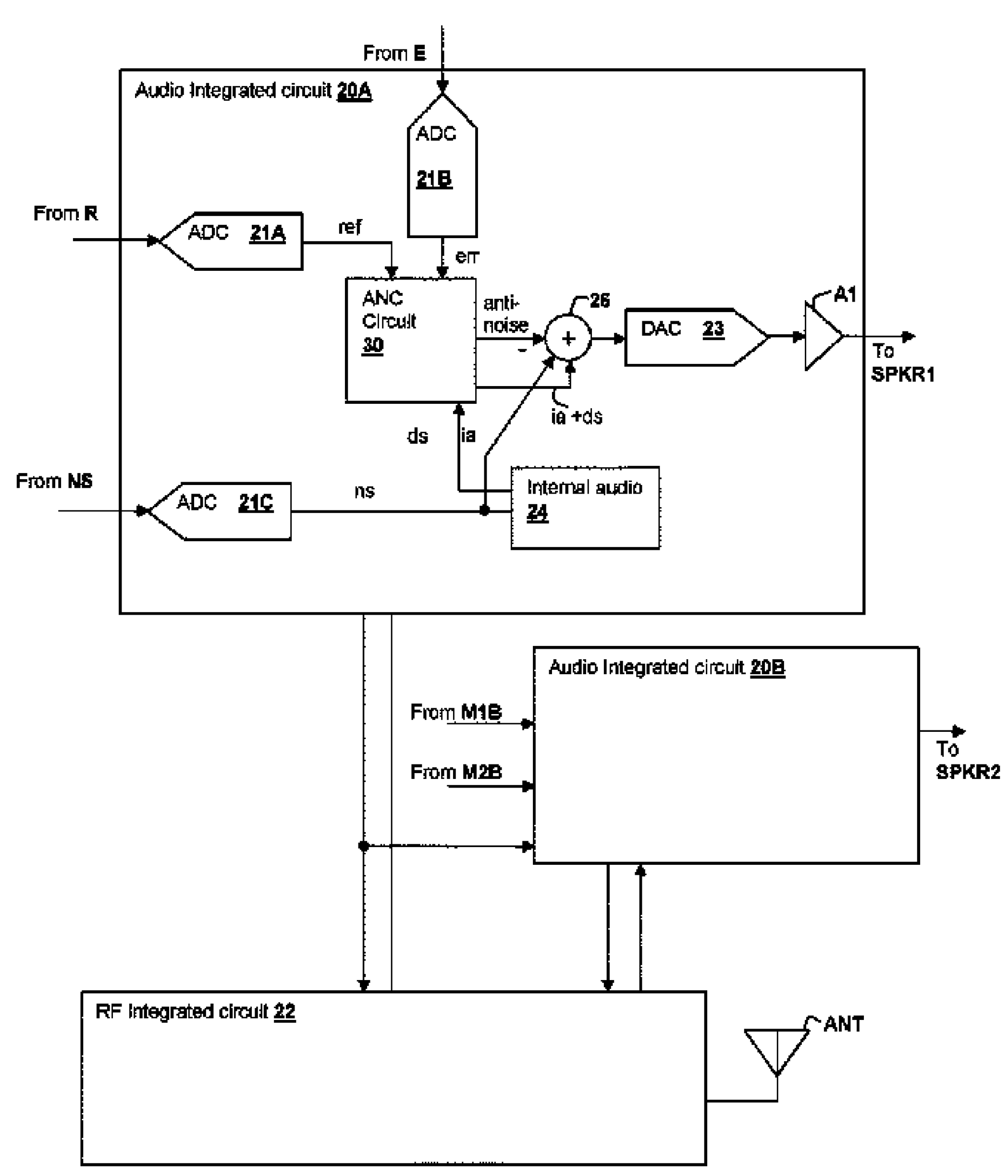
(57) **ABSTRACT**

A controller for an adaptive noise canceling (ANC) system simplifies the design of a stable control response by making the ANC gain of the system independent of a secondary path extending from a transducer of the ANC system to a sensor of the ANC system that measures the ambient noise. The controller includes a fixed filter having a predetermined fixed response, and a variable filter coupled together. The variable response filter compensates for variations of a transfer function of a secondary path that includes at least a path from a transducer of the ANC system to a sensor of the ANC system, so that the ANC gain is independent of the variations in the transfer function of the secondary path.

17 Claims, 14 Drawing Sheets



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WO	WO 2004017303	A1	2/2004
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WO	WO 2006128768	A1	12/2006
WO	WO 2007007916	A1	1/2007
WO	WO 2007011337		1/2007
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WO	WO 2015038255	A1	3/2015
WO	WO 2015088639	A1	6/2015
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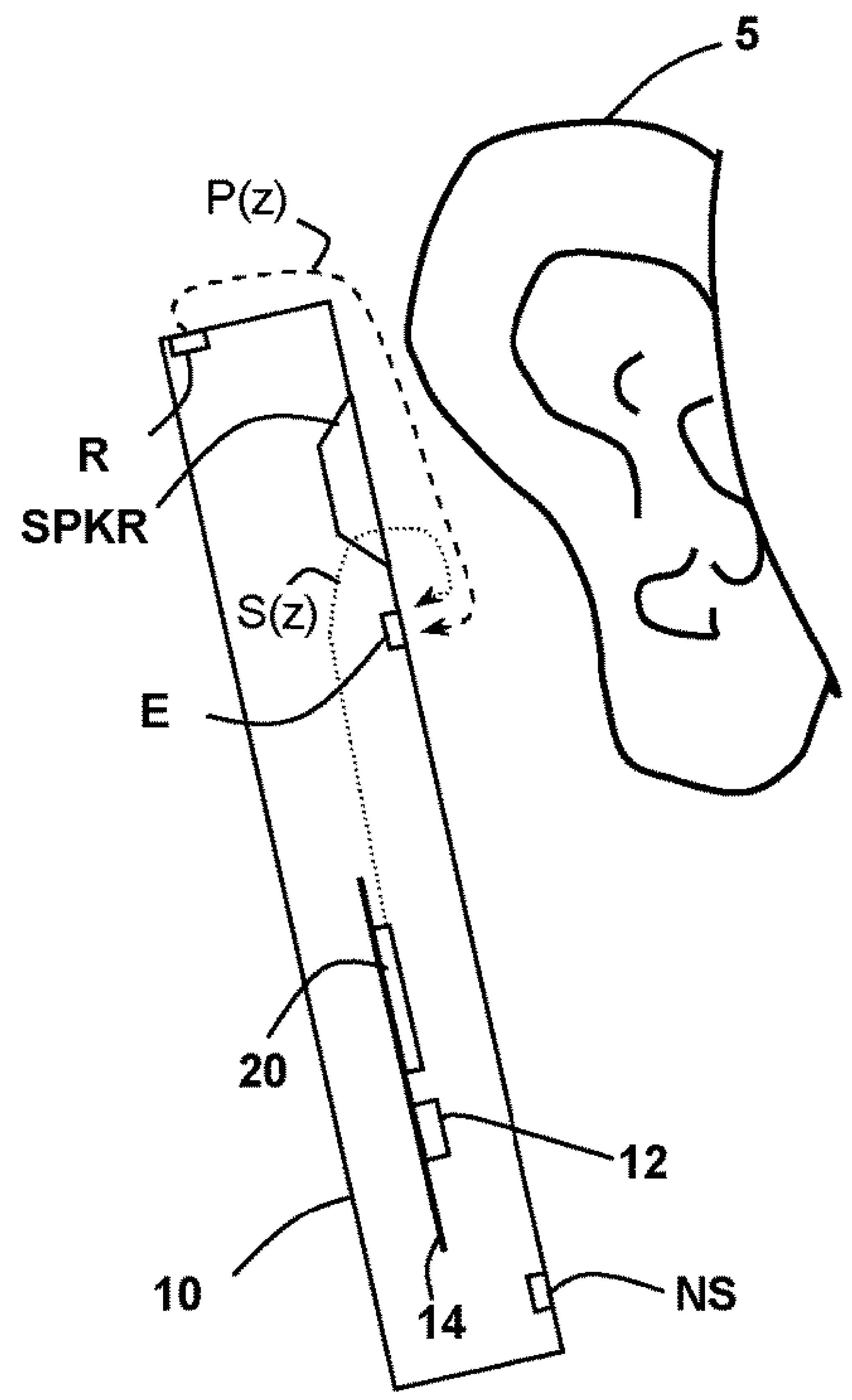

5
P(z)
R
SPKR
S(z)
E
20
12
10
14
NS

Fig. 1A

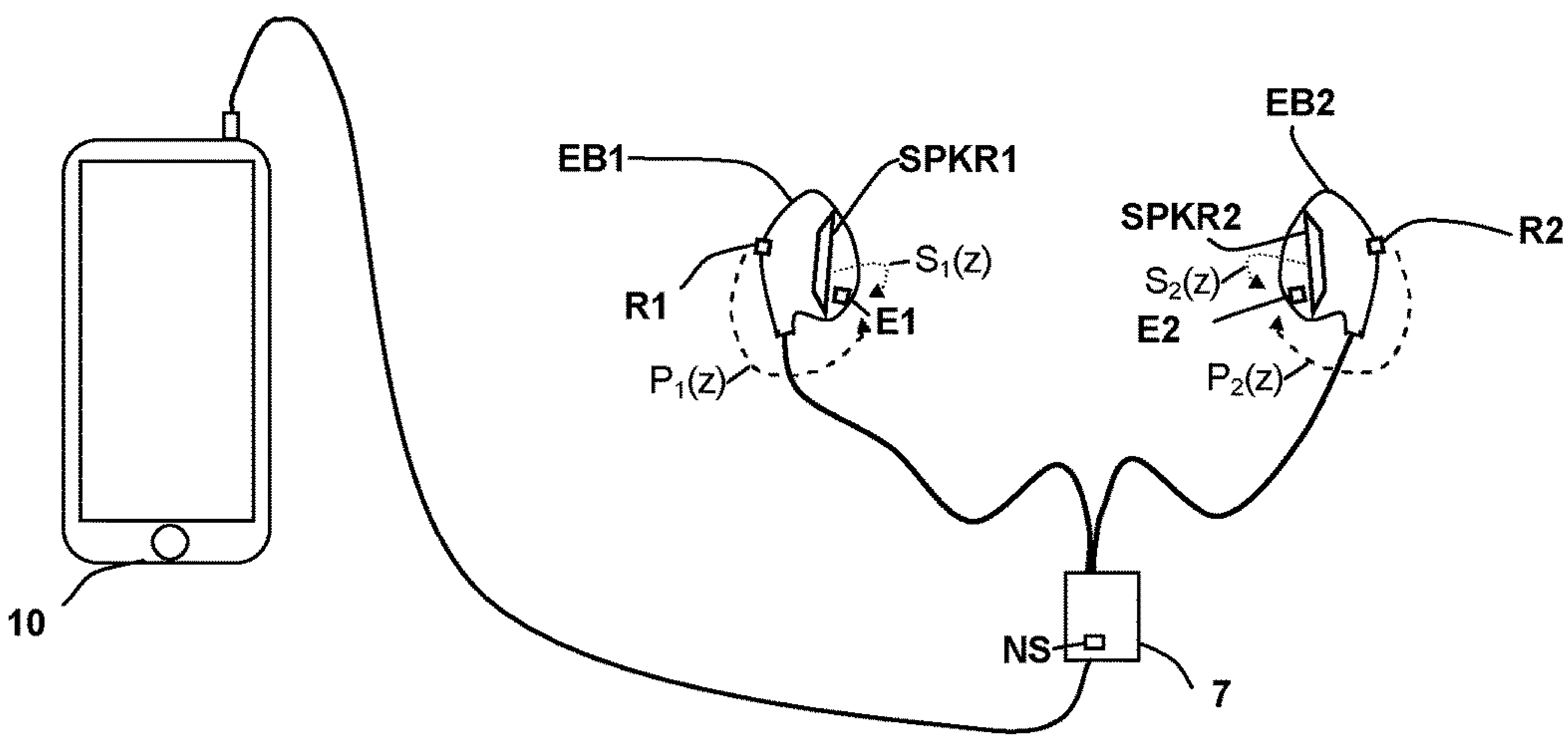
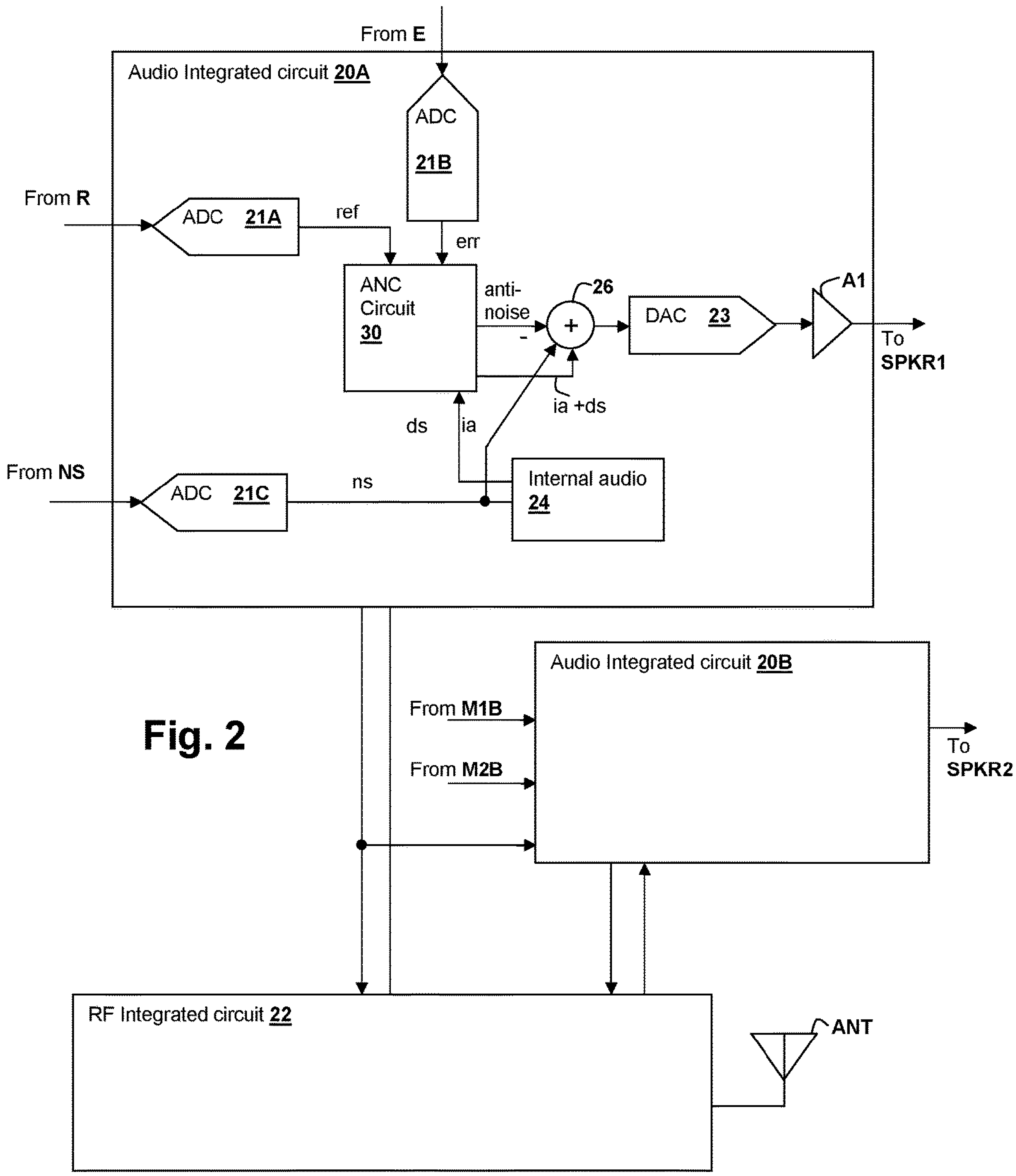
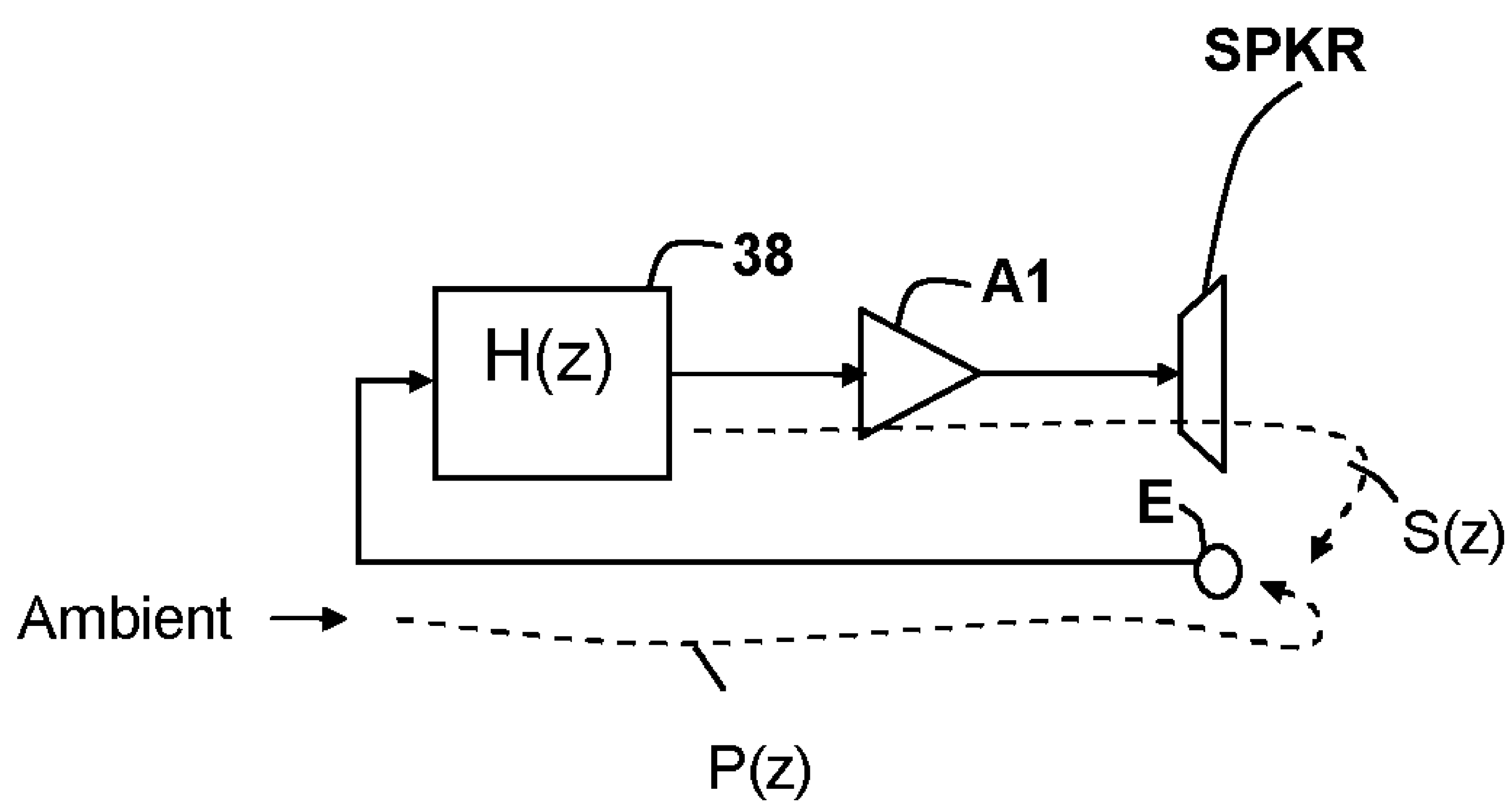

EB1
SPKR1
R1
$S_1(z)$
E1
$P_1(z)$
EB2
SPKR2
R2
$S_2(z)$
E2
$P_2(z)$
10
NS
7

Fig. 1B



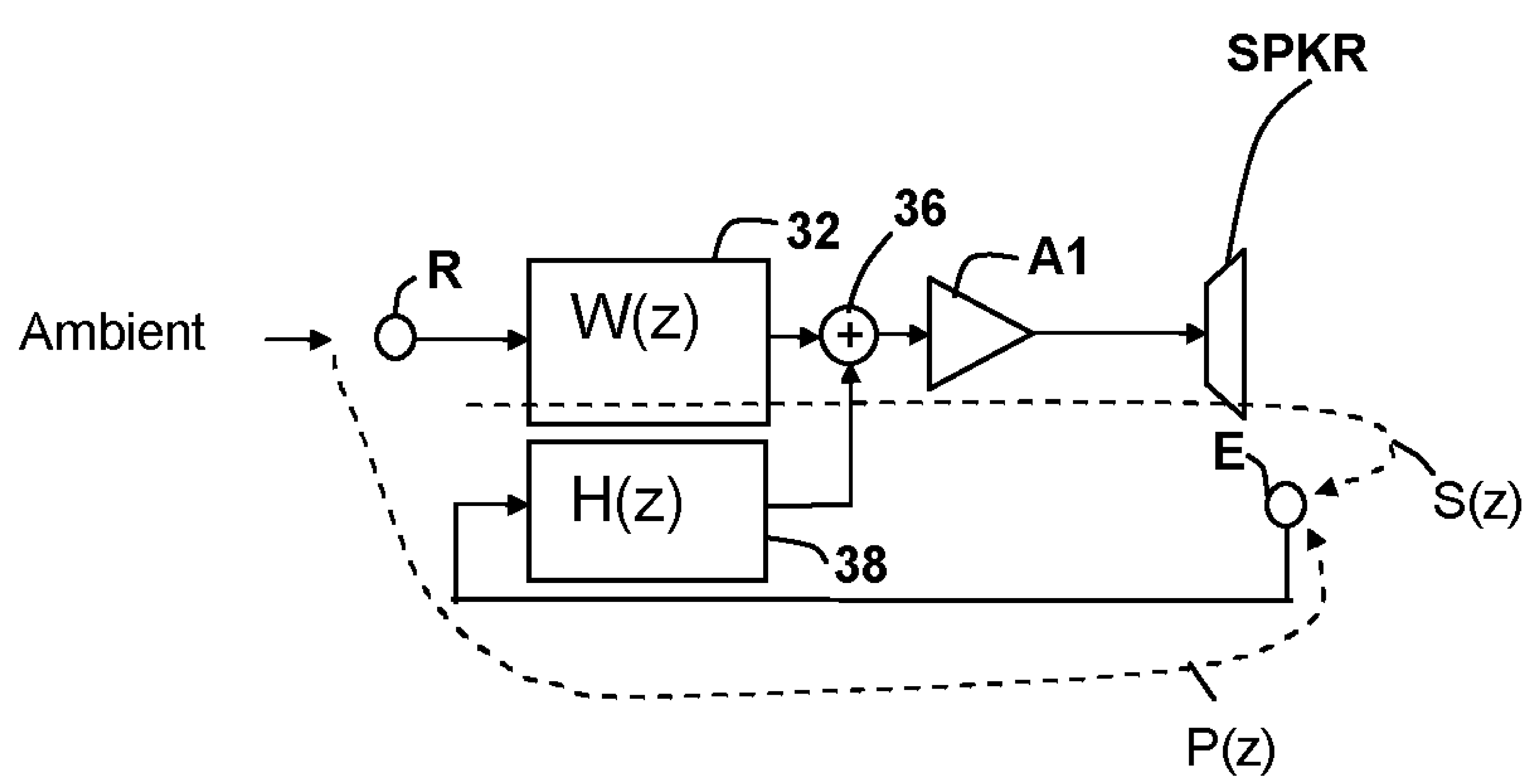
From E
Audio Integrated circuit 20A
ADC
21B
From R
ADC 21A
ref
err
ANC
Circuit
30
anti-
noise
-
26
DAC 23
A1
To
SPKR1
ia +ds
ds
ia
From NS
ADC 21C
ns
Internal audio
24
Audio Integrated circuit 20B
From M1B
From M2B
To
SPKR2
RF Integrated circuit 22
ANT

Fig. 2



SPKR
38
A1
H(z)
E
S(z)
Ambient
P(z)

Fig. 3A



SPKR
32
36
A1
R
W(z)
Ambient
E
S(z)
H(z)
38
P(z)

Fig. 3B

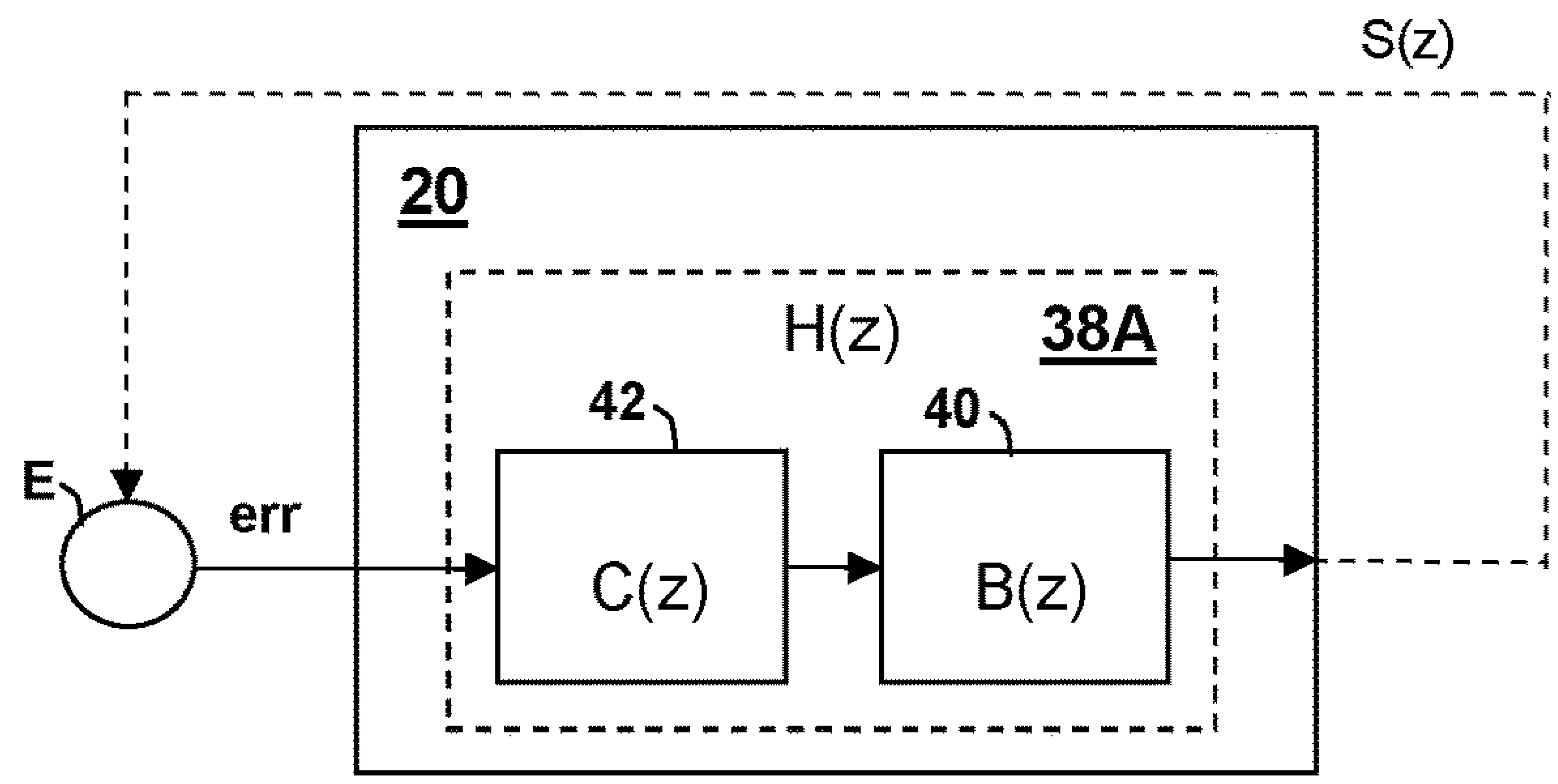


Fig. 4A

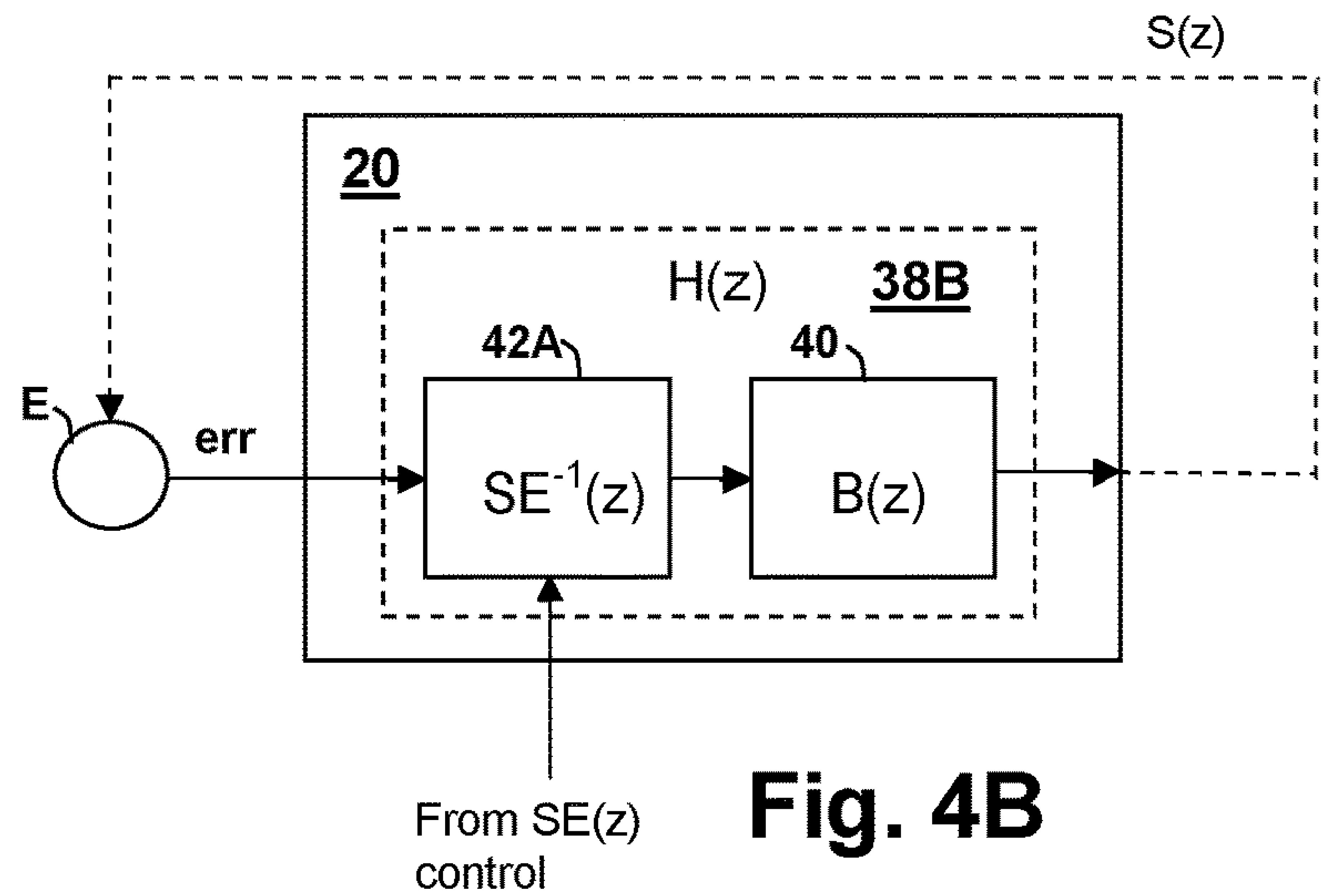


Fig. 4B

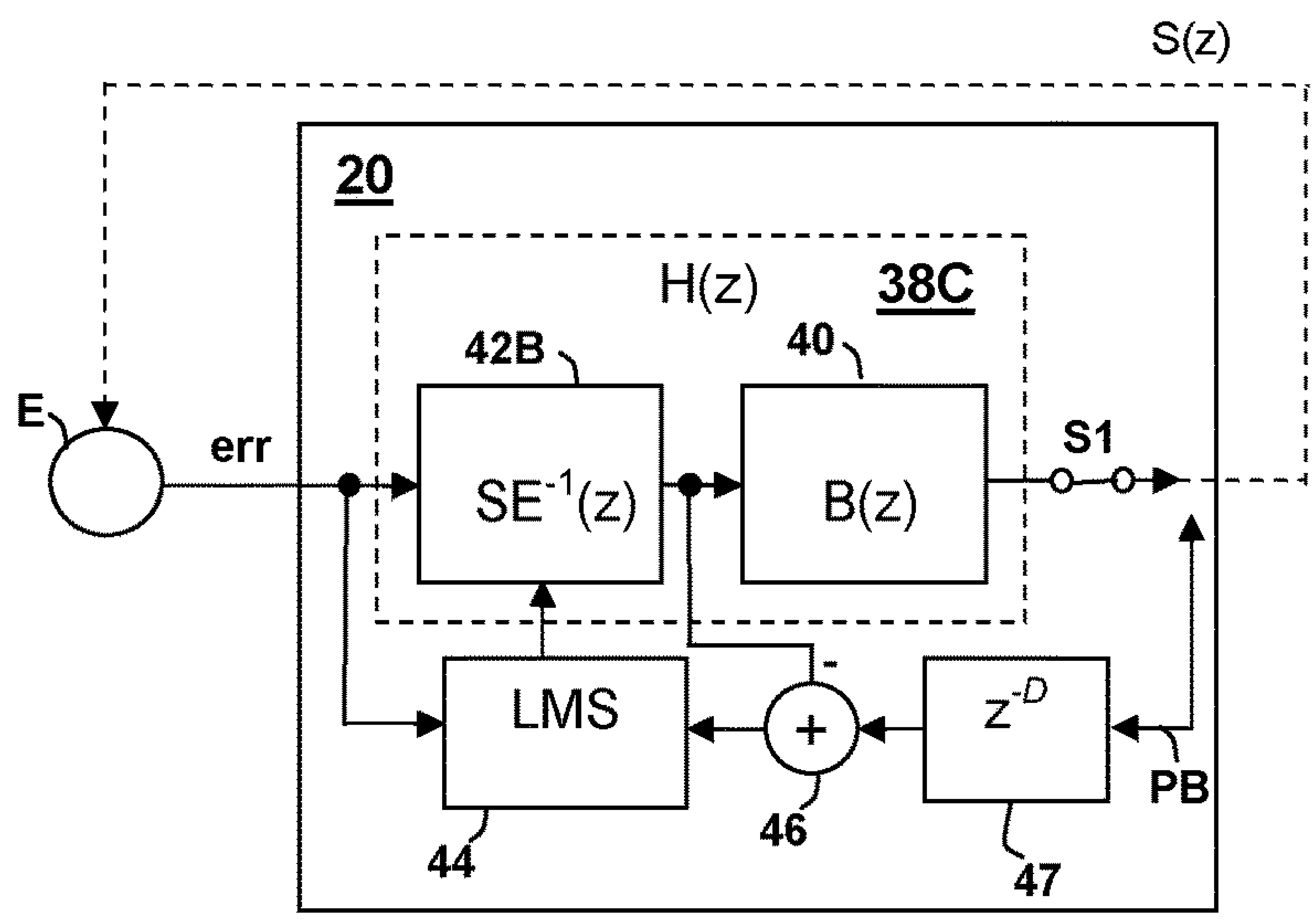
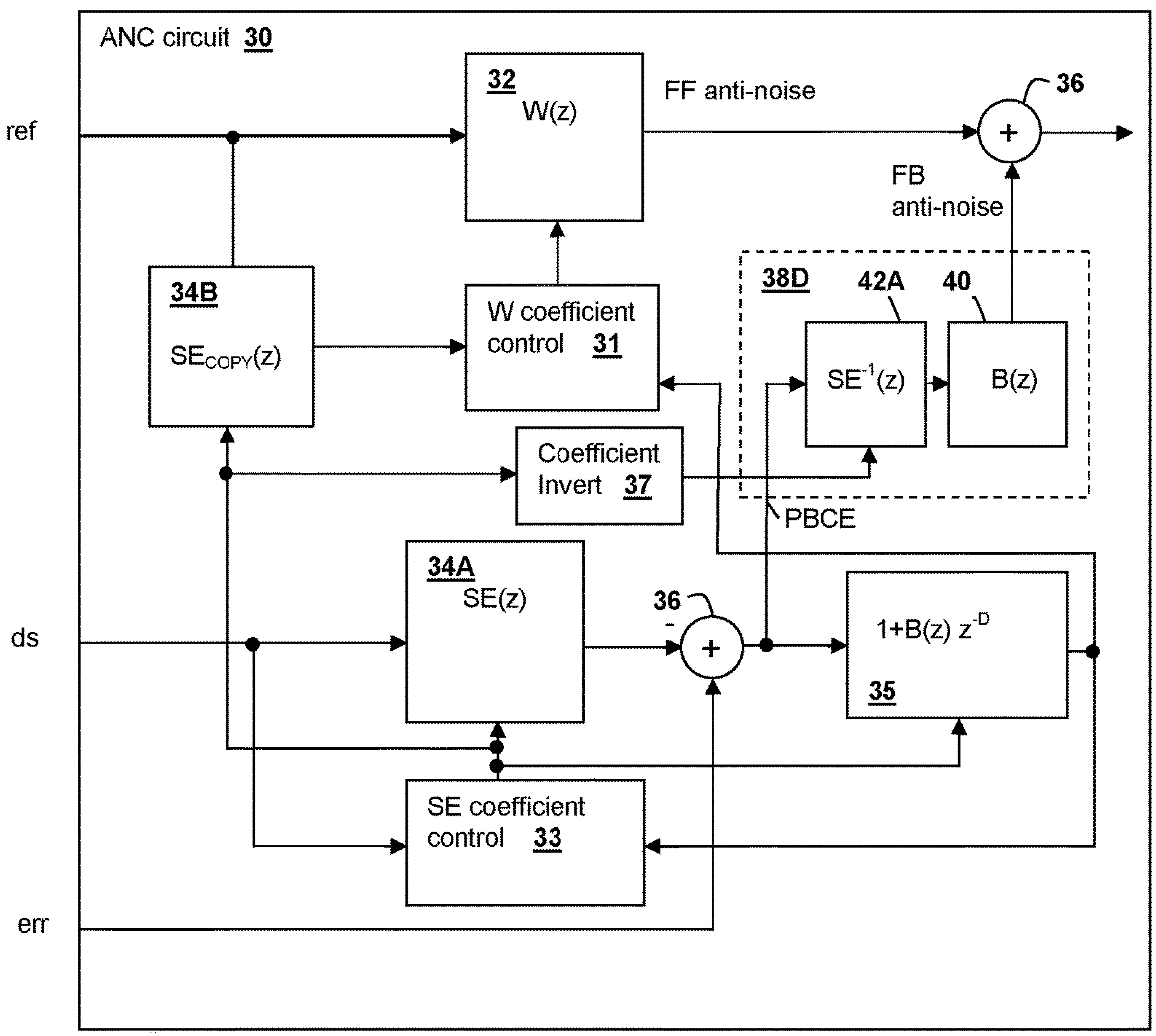


Fig. 4C



ANC circuit 30
ref
32
W(z)
FF anti-noise
36
FB
anti-noise
34B
SECOPY(z)
W coefficient
control 31
38D
42A
40
SE-1(z)
B(z)
Coefficient
Invert 37
PBCE
34A
SE(z)
ds
36
-
+
1+B(z) z-D
35
SE coefficient
control 33
err

Fig. 4D

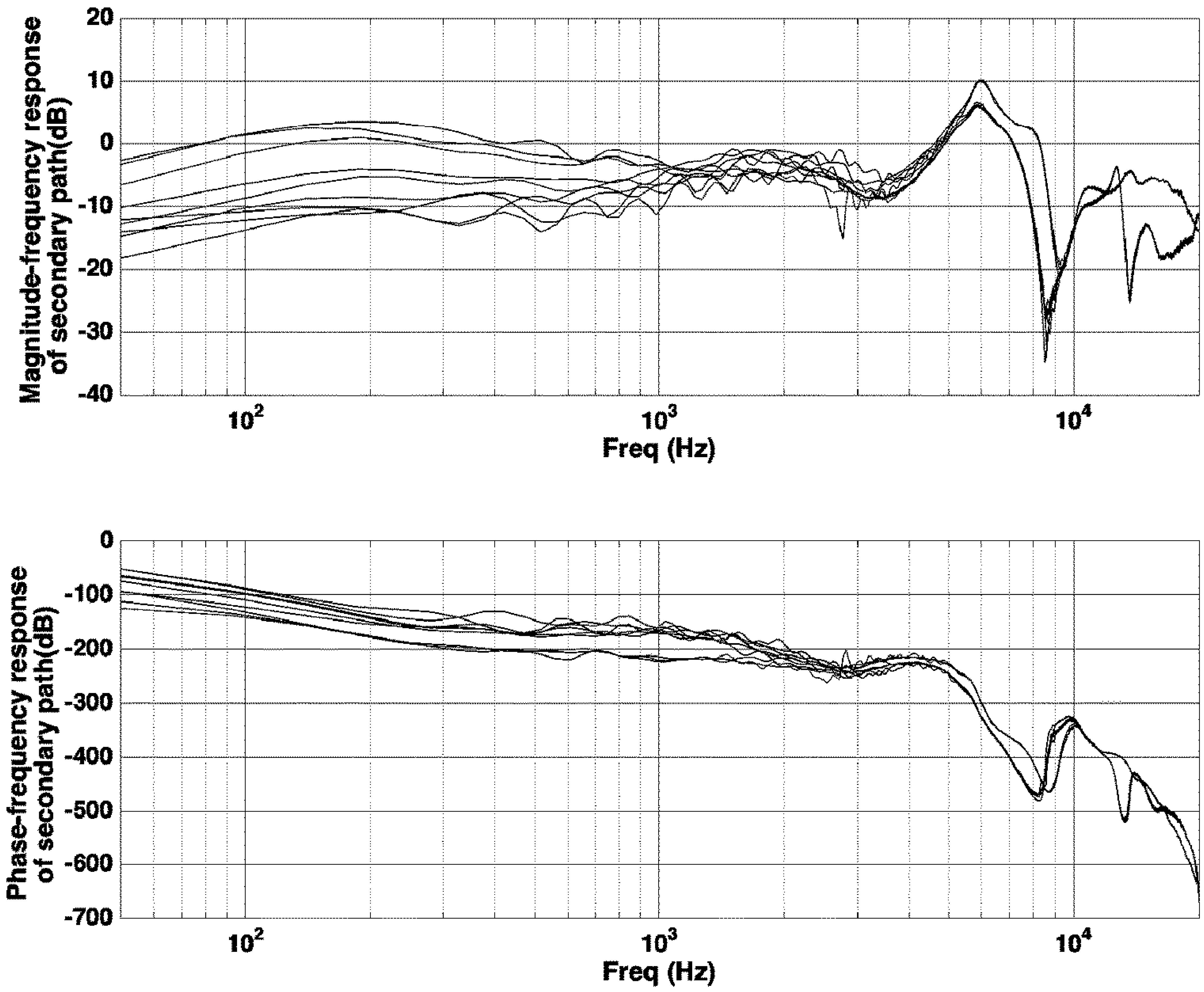

Magnitude-frequency response of secondary path(dB)
20
10
0
-10
-20
-30
-40
10^2
10^3
10^4
Freq (Hz)
Phase-frequency response of secondary path(dB)
0
-100
-200
-300
-400
-500
-600
-700
10^2
10^3
10^4
Freq (Hz)

Fig. 5A

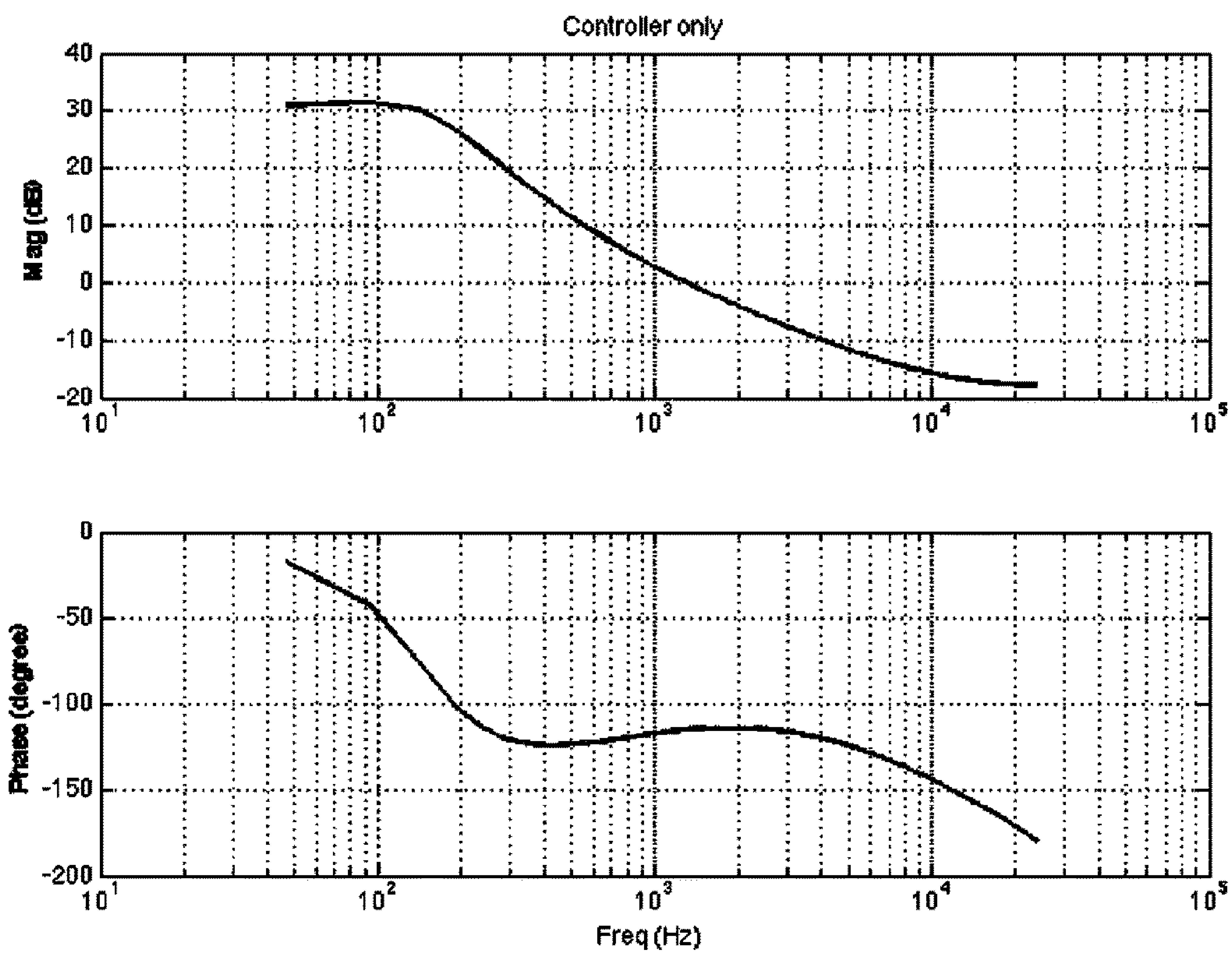

Controller only
40
30
20
10
0
-10
-20
Mag (dB)
10^1
10^2
10^3
10^4
10^5
0
-50
-100
-150
-200
Phase (degree)
10^1
10^2
10^3
10^4
10^5
Freq (Hz)

Fig. 5B

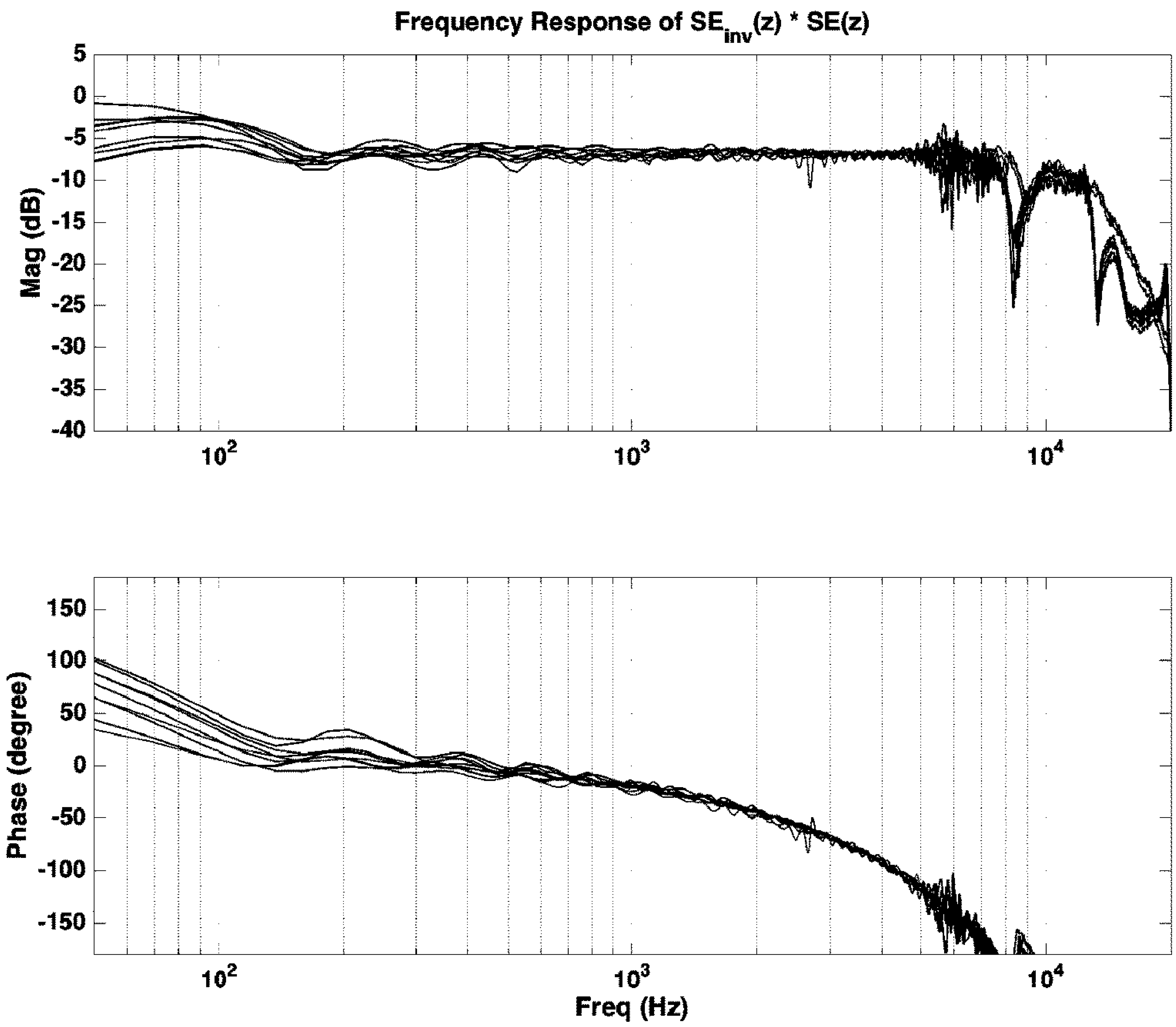

Frequency Response of $SE_{inv}(z)$ * SE(z)
Mag (dB)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
10^2
10^3
10^4
Phase (degree)
150
100
50
0
-50
-100
-150
10^2
10^3
10^4
Freq (Hz)

Fig. 5C

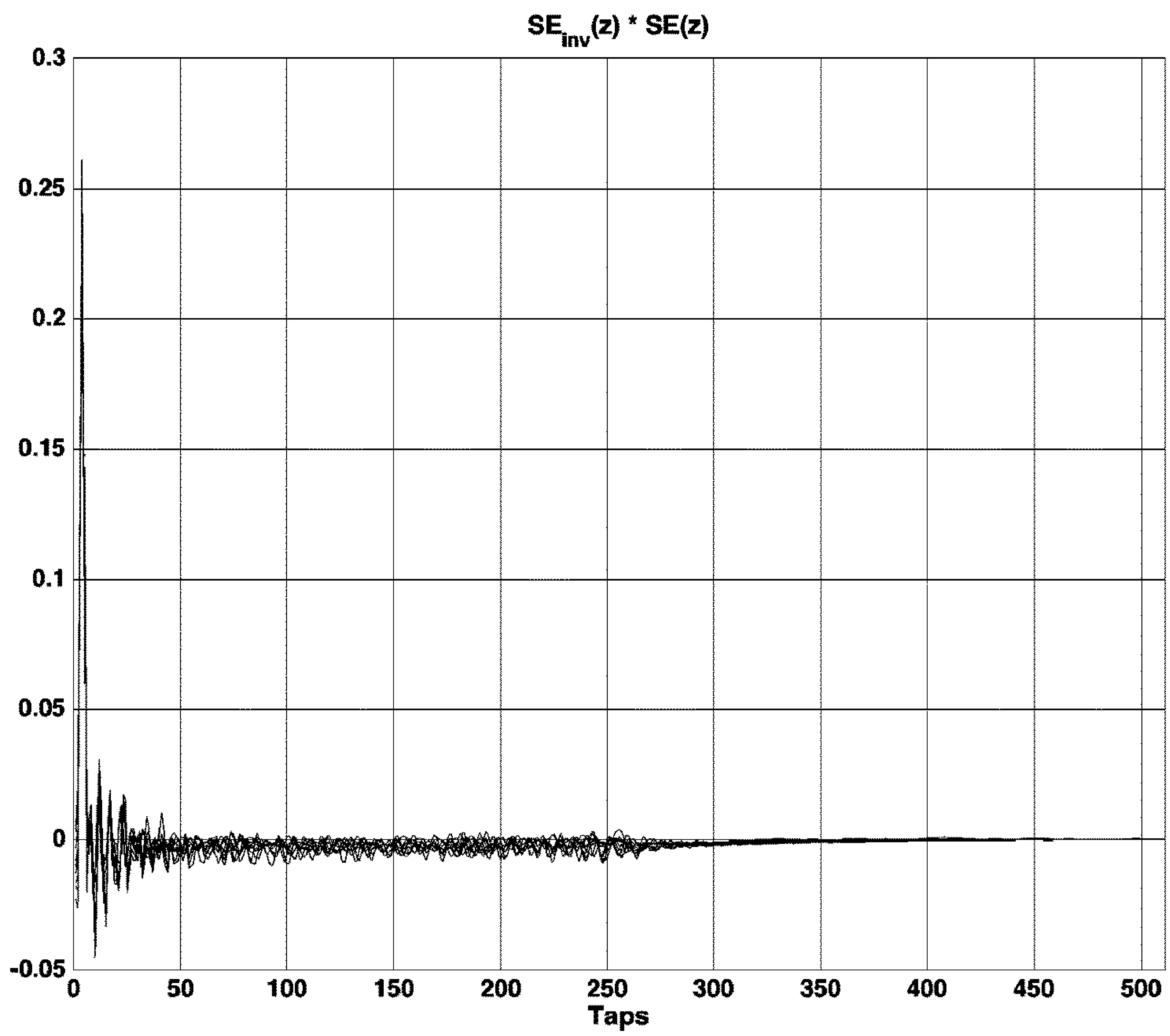

$SE_{inv}(z)$ * SE(z)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
50
100
150
200
250
300
350
400
450
500
Taps

Fig. 5D

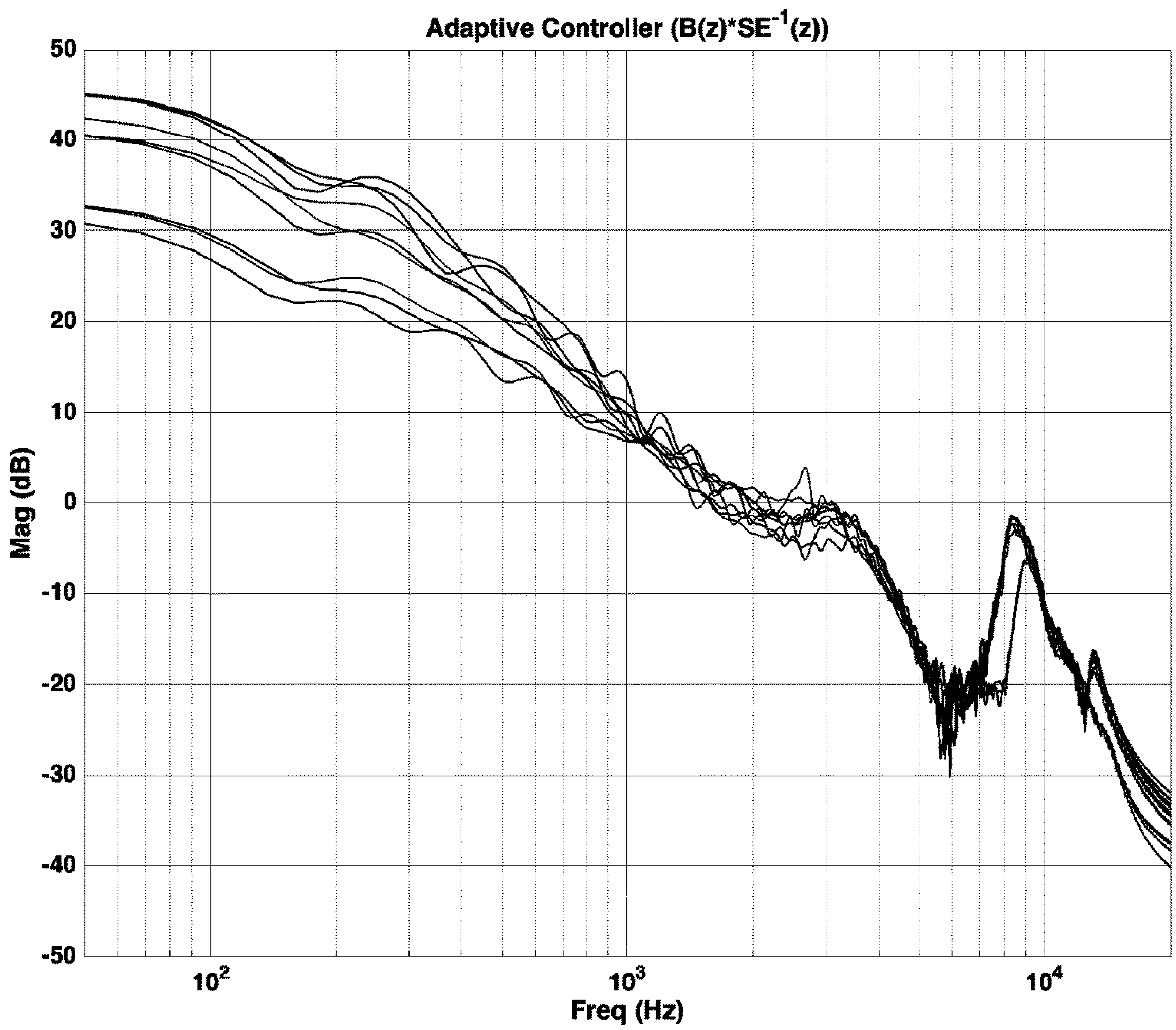
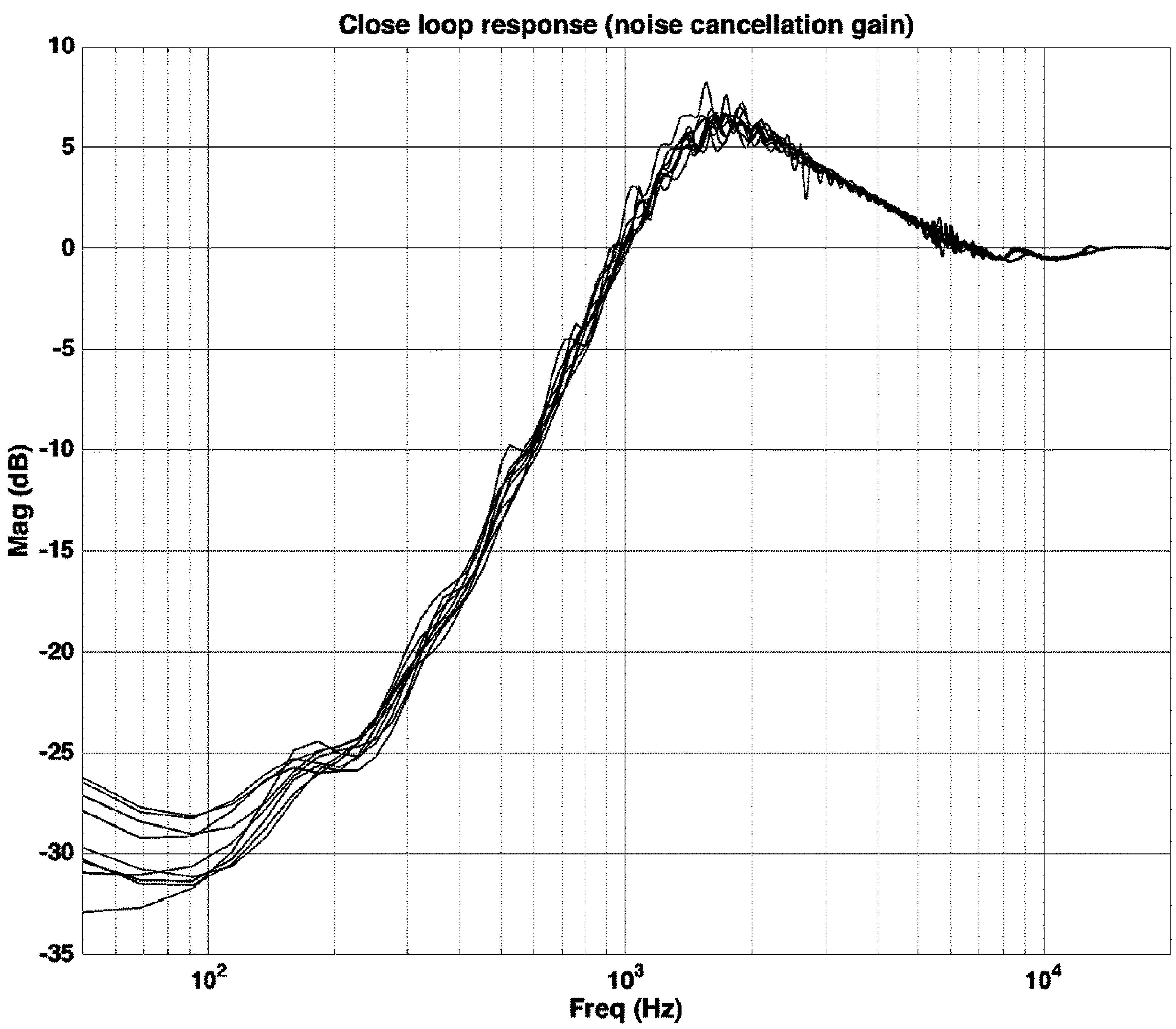

Adaptive Controller (B(z)*SE^{-1}(z))
50
40
30
20
10
0
-10
-20
-30
-40
-50
Mag (dB)
10^2
10^3
10^4
Freq (Hz)

Fig. 5E



Close loop response (noise cancellation gain)
10
5
0
-5
-10
-15
-20
-25
-30
-35
Mag (dB)
10^2
10^3
10^4
Freq (Hz)

Fig. 5F

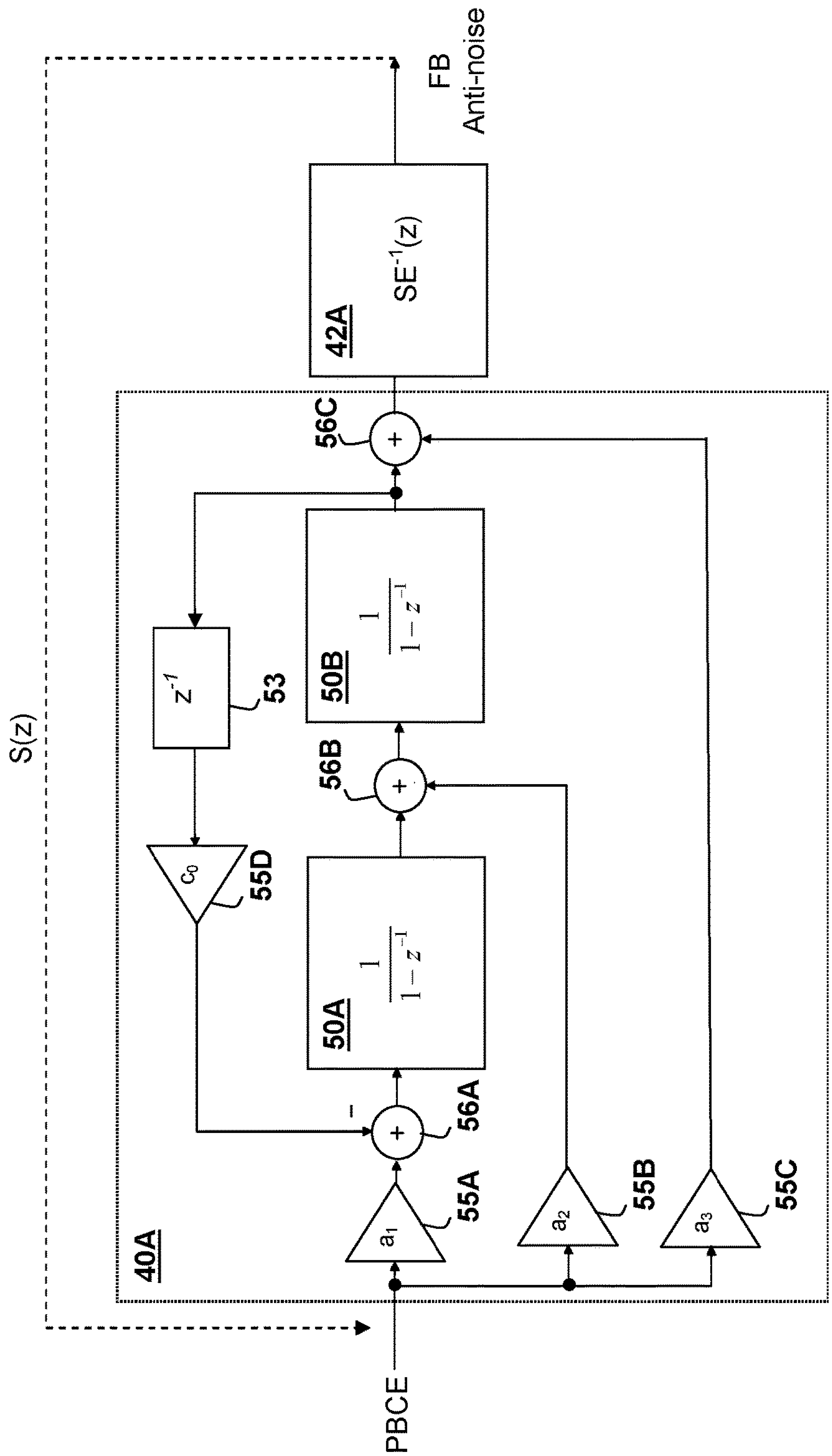

FB
Anti-noise
42A
SE-1(z)
56C
50B
1/(1 − z−1)
53
z-1
S(z)
56B
55D
c0
50A
1/(1 − z−1)
56A
−
55A
55B
55C
a1
a2
a3
40A
PBCE

Fig. 6

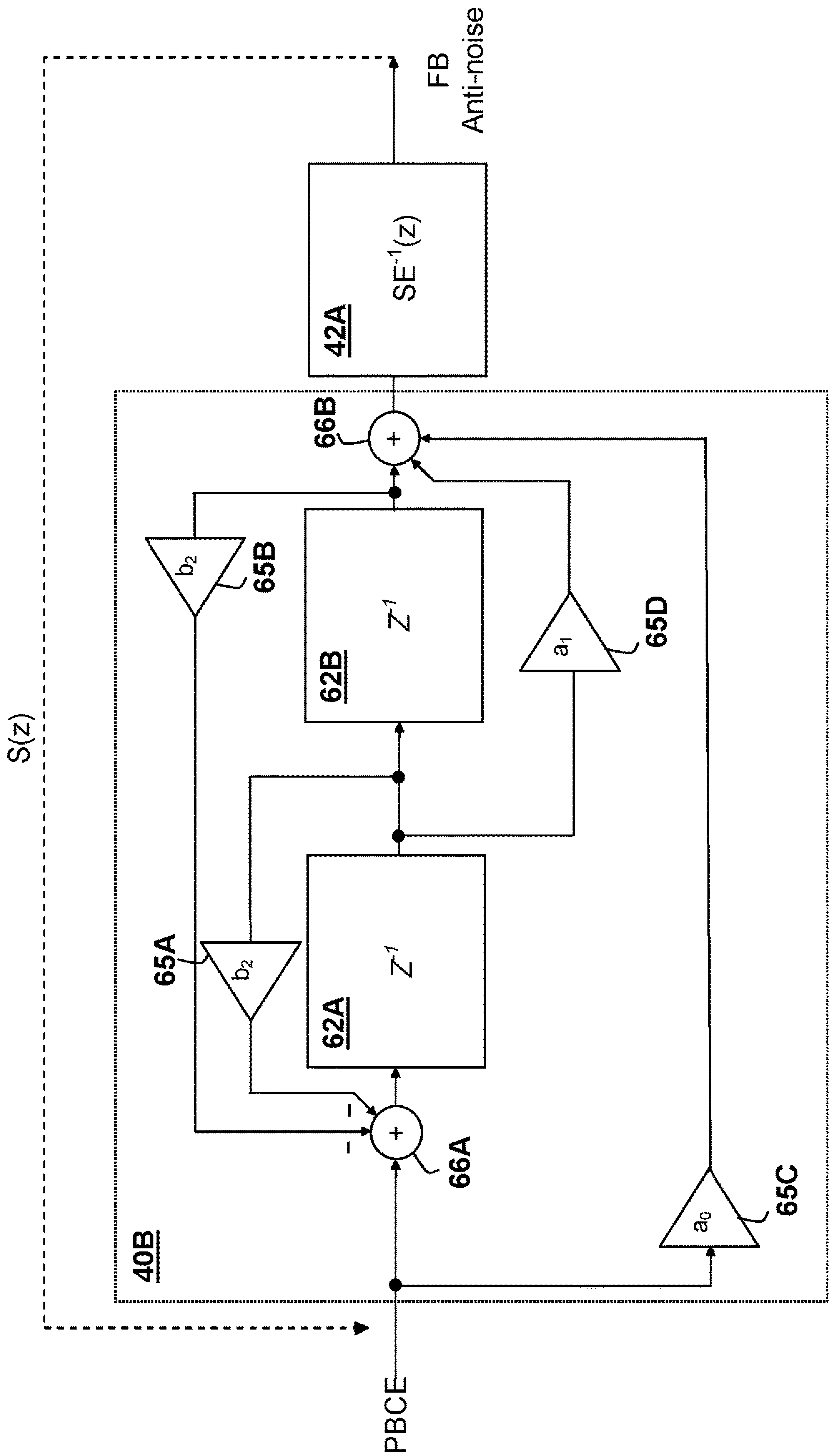

FB
Anti-noise
42A
SE-1(z)
40B
66B
62B
Z-1
65B
b2
65D
a1
S(z)
65A
b2
62A
Z-1
66A
65C
a0
PBCE

Fig. 7

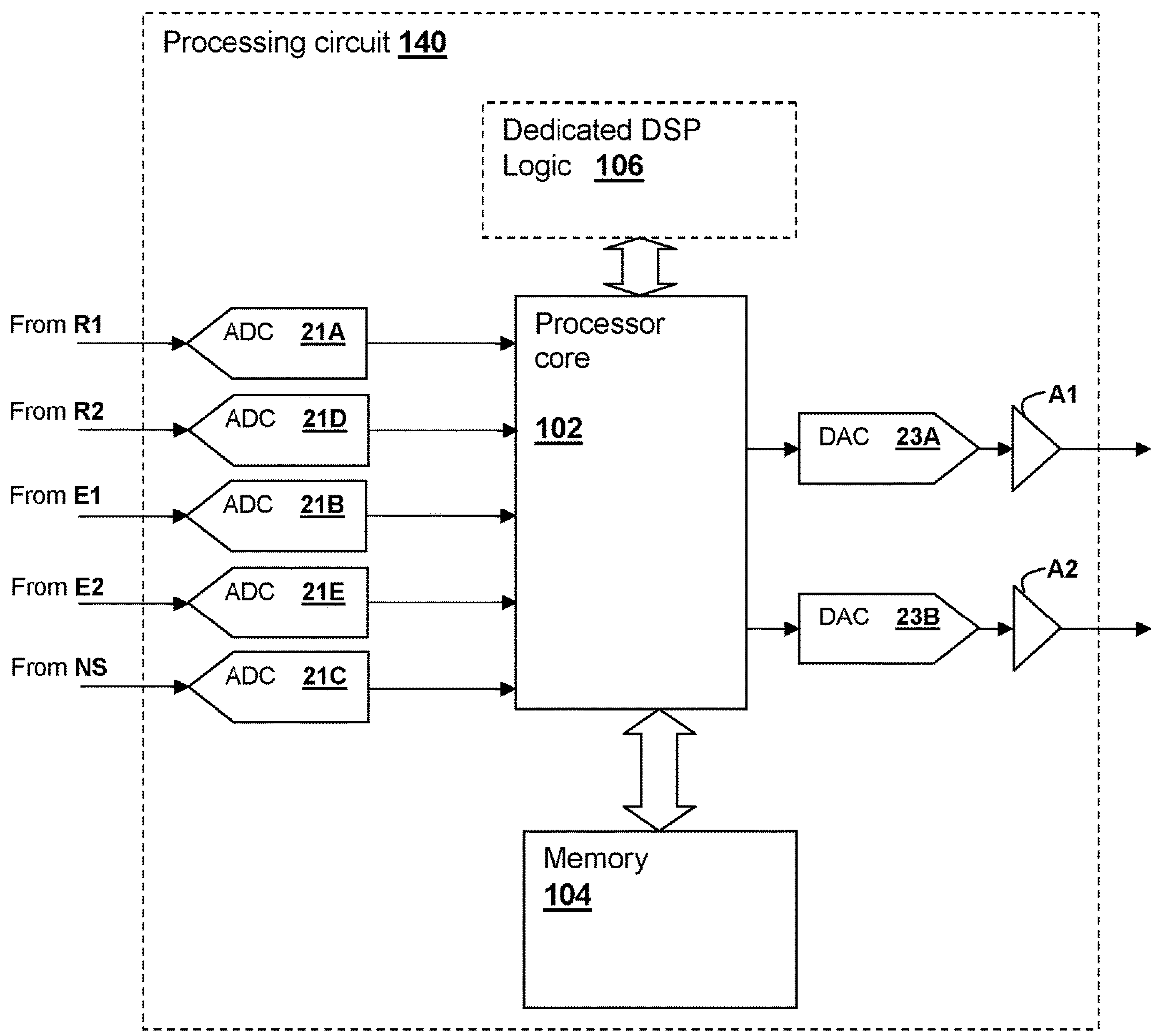

Processing circuit 140
Dedicated DSP Logic 106
From R1
From R2
From E1
From E2
From NS
ADC 21A
ADC 21D
ADC 21B
ADC 21E
ADC 21C
Processor core 102
DAC 23A
DAC 23B
A1
A2
Memory 104

Fig. 8

FEEDBACK ADAPTIVE NOISE CANCELLATION (ANC) CONTROLLER AND METHOD HAVING A FEEDBACK RESPONSE PARTIALLY PROVIDED BY A FIXED-RESPONSE FILTER

This U.S. Patent Application Claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Ser. No. 62/207,657 filed on Aug. 20, 2015.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The field of representative embodiments of this disclosure relates to methods and systems for adaptive noise cancellation (ANC), and in particular to an ANC feedback controller in which the feedback response is provided by a fixed transfer function feedback filter and a variable response filter.

2. Background of the Invention

Wireless telephones, such as mobile/cellular telephones, cordless telephones, and other consumer audio devices, such as MP3 players, are in widespread use. Performance of such devices with respect to intelligibility can be improved by providing noise canceling using a microphone to measure ambient acoustic events and then using signal processing to insert an anti-noise signal into the output of the device to cancel the ambient acoustic events.

In many noise cancellation systems, it is desirable to include both feed-forward noise cancellation by using a feed-forward adaptive filter for generating a feed-forward anti-noise signal from a reference microphone signal configured to measure ambient sounds and feedback noise cancellation by using a fixed-response feedback filter for generating a feedback noise cancellation signal to be combined with the feed-forward anti-noise signal. In other noise cancellation systems, only feedback noise cancellation is provided. An adaptive feedback noise cancelling system includes an adaptive filter that generates an anti-noise signal from an output of a sensor that senses the noise to be canceled and that is provided to an output transducer for reproduction to cancel the noise.

In any ANC system having a feedback noise-canceling path, the secondary path, which is the electro-acoustic path at least extending from the output transducer that reproduces the anti-noise signal generated by the ANC system to the output signal provided by the input sensor that measures the ambient noise to be canceled, determines a portion of the necessary feedback response to provide proper noise-canceling. In ANC systems in which the acoustic environment around the output transducer and input sensor varies greatly, such as in a mobile telephone where the telephone's position with respect to the user's ear changes the coupling between the telephone's speaker and a microphone used to measure the ambient noise, the secondary path response varies as well. Since the feedback path transfer function for generating a proper anti-noise signal is dependent on the secondary path response, it is difficult to provide an ANC controller that is stable for all possible configurations of the acoustic path between the output transducer and input sensor that may be present in an actual implementation.

Therefore, it would be desirable to provide an ANC controller with improved stability in ANC feedback and feed-forward/feedback ANC systems.

SUMMARY OF THE INVENTION

The above-stated objective of providing an ANC controlled with improved stability, is accomplished in an ANC controller, a method of operation, and an integrated circuit.

The ANC controller includes a fixed filter having a predetermined fixed transfer function and a variable-response filter coupled together. The fixed transfer function relates to and maintains stability of a compensated feedback loop and contributes to an ANC gain of the ANC system. The response of the variable-response filter compensates for variation of a transfer function of a secondary path that includes at least a path from a transducer of the ANC system to a sensor of the ANC system, so that the ANC gain is independent of the variation of the transfer function of the secondary path.

The description below sets forth example embodiments according to this disclosure. Further embodiments and implementations will be apparent to those having ordinary skill in the art. Persons having ordinary skill in the art will recognize that various equivalent techniques may be applied in lieu of, or in conjunction with, the embodiments discussed below, and all such equivalents are encompassed by the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is an illustration of a wireless telephone **10**, which is an example of a personal audio device in which the techniques disclosed herein can be implemented.

FIG. **1**B is an illustration of a wireless telephone **10** coupled to a pair of earbuds EB**1** and EB**2**, which is an example of a personal audio system in which the techniques disclosed herein can be implemented.

FIG. **2** is a block diagram of circuits within wireless telephone **10** and/or earbud EB of FIG. **1**A.

FIG. **3**A is an illustration of electrical and acoustical signal paths in FIG. **1**A and FIG. **1**B including a feedback acoustic noise canceler.

FIG. **3**B is an illustration of electrical and acoustical signal paths in FIG. **1**A and FIG. **1**B including a hybrid feed-forward/feedback acoustic noise canceler.

FIGS. **4**A-**4**D are block diagrams depicting various examples of ANC circuits that can be used to implement ANC circuit **30** of audio integrated circuits **20**A-**20**B of FIG. **2**.

FIGS. **5**A-**5**F are graphs depicting acoustic and electric responses within the ANC systems disclosed herein.

FIG. **6** is a block diagram depicting a digital filter that can be used to implement fixed response filter **40** within the circuits depicted in FIGS. **4**A-**4**D.

FIG. **7** is a block diagram depicting an alternative digital filter that can be used to implement fixed response filter **40** within the circuits depicted in FIGS. **4**A-**4**D.

FIG. **8** is a block diagram depicting signal processing circuits and functional blocks that can be used to implement the circuits depicted in FIG. **2** and FIGS. **4**A-**4**D.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENT

The present disclosure encompasses noise canceling techniques and circuits that can be implemented in a personal audio device, such as a wireless telephone, tablet, note-book computer, noise-canceling headphones, as well as in other noise-canceling circuits. The personal audio device includes an ANC circuit that measures the ambient acoustic environment with a sensor and generates an anti-noise signal that is output via a speaker or other transducer to cancel ambient acoustic events. The example ANC circuits shown herein include a feedback filter and may include a feed-forward filter that are used to generate the anti-noise signal from the sensor output. A secondary path, including the acoustic path from the transducer back to the sensor, closes a feedback loop around an ANC feedback path that extends through the feedback filter, and thus the stability of the feedback loop is dependent on the characteristics of the secondary path. The secondary path involves structures around and between the transducer and sensor, thus for devices such as a wireless telephone, the response of the secondary path varies with the user and the position of the device with respect to the user's ear(s). To provide stability over a range of variable secondary paths, the instant disclosure uses a pair of filters, one having a fixed predetermined response and the other having a variable response that compensates for secondary path variations. The fixed predetermined response is selected to provide stability over the range of secondary path responses expected for the device, contributes to the acoustic noise cancellation and generally maximizes the range over which the acoustic noise cancelation operates.

Referring now to FIG. **1**A, an exemplary wireless telephone **10** is shown in proximity to a human ear **5**. Illustrated wireless telephone **10** is an example of a device in which techniques illustrated herein may be employed, but it is understood that not all of the elements or configurations embodied in illustrated wireless telephone **10**, or in the circuits depicted in subsequent illustrations, are required to practice what is claimed. Wireless telephone **10** includes a transducer such as speaker SPKR that reproduces distant speech received by wireless telephone **10**, along with other local audio events such as ringtones, stored audio program material, near-end speech (i.e., the speech of the user of wireless telephone **10**), sources from web-pages or other network communications received by wireless telephone **10** and audio indications such as battery low and other system event notifications. A near-speech microphone NS is provided to capture near-end speech, which is transmitted from wireless telephone **10** to the other conversation participant (s).

Wireless telephone **10** includes adaptive noise canceling (ANC) circuits and features that inject an anti-noise signal into speaker SPKR to improve intelligibility of the distant speech and other audio reproduced by speaker SPKR. A reference microphone R may be provided for measuring the ambient acoustic environment and is positioned away from the typical position of a user's mouth, so that the near-end speech is minimized in the signal produced by reference microphone R. A third microphone, error microphone E, may be provided in order to further improve the ANC operation by providing a measure of the ambient audio combined with the audio reproduced by speaker SPKR close to ear **5**, when wireless telephone **10** is in proximity to ear **5**. A circuit **14** within wireless telephone **10** may include an audio CODEC integrated circuit **20** that receives the signals from reference microphone R, near-speech microphone NS, and error microphone E and interfaces with other integrated circuits such as an RF integrated circuit **12** containing the wireless telephone transceiver. In some embodiments of the disclosure, the circuits and techniques disclosed herein may be incorporated in a single integrated circuit that contains control circuits and other functionality for implementing the entirety of the personal audio device, such as an MP3 player-on-a-chip integrated circuit. In the depicted embodiments and other embodiments, the circuits and techniques disclosed herein may be implemented partially or fully in software and/or firmware embodied in computer-readable storage media and executable by a processor circuit or other processing device such as a microcontroller.

In general, the ANC techniques disclosed herein measure ambient acoustic events (as opposed to the output of speaker SPKR and/or the near-end speech) impinging on error microphone E and/or reference microphone R. The ANC processing circuits of illustrated wireless telephone **10** adapt an anti-noise signal generated from the output of error microphone E and/or reference microphone R to have a characteristic that minimizes the amplitude of the ambient acoustic events present at error microphone E. Since acoustic path P(z) extends from reference microphone R to error microphone E, the ANC circuits are effectively estimating acoustic path P(z) combined with removing effects of an electro-acoustic path S(z). Electro-acoustic path S(z) represents the response of the audio output circuits of CODEC IC **20** and the acoustic/electric transfer function of speaker SPKR including the coupling between speaker SPKR and error microphone E in the particular acoustic environment. Electro-acoustic path S(z) is affected by the proximity and structure of ear **5** and other physical objects and human head structures that may be in proximity to wireless telephone **10**, when wireless telephone **10** is not firmly pressed to ear **5**. While the illustrated wireless telephone **10** includes a two microphone ANC system with a third near-speech microphone NS, other systems that do not include separate error and reference microphones can implement the above-described techniques. Alternatively, near-speech microphone NS can be used to perform the function of the reference microphone R in the above-described system. Also, in personal audio devices designed only for audio playback, near-speech microphone NS will generally not be included, and the near-speech signal paths in the circuits described in further detail below can be omitted without changing the scope of the disclosure. Also, the techniques disclosed herein can be applied in purely noise-canceling systems that do not reproduce a playback signal or conversation using the output transducer, i.e., those systems that only reproduce an anti-noise signal.

Referring now to FIG. **1**B, another wireless telephone configuration in which the techniques disclosed herein is shown. FIG. **1**B shows wireless telephone **10** and a pair of earbuds EB**1** and EB**2**, each attached to a corresponding ear of a listener. Illustrated wireless telephone **10** is an example of a device in which the techniques herein may be employed, but it is understood that not all of the elements or configurations illustrated in wireless telephone **10**, or in the circuits depicted in subsequent illustrations, are required. Wireless telephone **10** is connected to earbuds EB**1**, EB**2** by a wired or wireless connection, e.g., a BLUETOOTH™ connection (BLUETOOTH is a trademark of Bluetooth SIG, Inc.). Earbuds EB**1**, EB**2** each have a corresponding transducer, such as speaker SPKR**1**, SPKR**2**, which reproduce source audio including distant speech received from wireless telephone **10**, ringtones, stored audio program material, and injection of near-end speech (i.e., the speech of the user of wireless telephone **10**). The source audio also includes any other audio that wireless telephone **10** is required to reproduce, such as source audio from web-pages or other network communications received by wireless telephone **10** and audio indications such as battery low and other system event notifications. Reference microphones R**1**, R**2** are provided on a surface of the housing of respective earbuds EB**1**, EB**2** for measuring the ambient acoustic environment. Another pair of microphones, error microphones E**1**, E**2**, are provided in order to further improve the ANC operation by providing a measure of the ambient audio combined with the audio reproduced by respective speakers SPKR**1**, SPKR**2** close to corresponding ears **5**A, **5**B, when earbuds EB**1**, EB**2** are inserted in the outer portion of ears **5**A, **5**B. As in wireless telephone **10** of FIG. **1**A, wireless telephone **10** includes adaptive noise canceling (ANC) circuits and features that inject an anti-noise signal into speakers SPKR**1**, SPKR**2** to improve intelligibility of the distant speech and other audio reproduced by speakers SPKR**1**, SPKR**2**. In the depicted example, an ANC circuit within wireless telephone **10** receives the signals from reference microphones R**1**, R**2** and error microphones E**1**, E**2**. Alternatively, all or a portion of the ANC circuits disclosed herein may be incorporated within earbuds EB**1**, EB**2**. For example, each of earbuds EB**1**, EB**2** may constitute a stand-alone acoustic noise canceler including a separate ANC circuit. Near-speech microphone NS may be provided on the outer surface of a housing of one of earbuds EB**1**, EB**2**, on a boom affixed to one of earbuds EB**1**, EB**2**, or on a combox pendant **7** located between wireless telephone **10** and either or both of earbuds EB**1**, EB**2**, as shown.

As described above with reference to FIG. **1**A, the ANC techniques illustrated herein measure ambient acoustic events (as opposed to the output of speakers SPKR**1**, SPKR**2** and/or the near-end speech) impinging on error microphones E**1**, E**2** and/or reference microphones R**1**, R**2**. In the embodiment depicted in FIG. **1**B, the ANC processing circuits of integrated circuits within earbuds EB**1**, EB**2**, or alternatively within wireless telephone **10** or combox pendant **7**, individually adapt an anti-noise signal generated from the output of the corresponding reference microphone R**1**, R**2** to have a characteristic that minimizes the amplitude of the ambient acoustic events at the corresponding error microphone E**1**, E**2**. Since acoustic path $P_1(z)$ extends from reference microphone R**1** to error microphone E, the ANC circuit in audio integrated circuit **20**A is essentially estimating acoustic path $P_1(z)$ combined with removing effects of an electro-acoustic path $S_1(z)$ that represents the response of the audio output circuits of audio integrated circuit **20**A and the acoustic/electric transfer function of speaker SPKR**1**. The estimated response includes the coupling between speaker SPKR**1** and error microphone E**1** in the particular acoustic environment which is affected by the proximity and structure of ear **5**A and other physical objects and human head structures that may be in proximity to earbud EB**1**. Similarly, audio integrated circuit **20**B estimates acoustic path $P_2(z)$ combined with removing effects of an electro-acoustic path $S_2(z)$ that represents the response of the audio output circuits of audio integrated circuit **20**B and the acoustic/electric transfer function of speaker SPKR**2**. As used in this disclosure, the terms "headphone" and "speaker" refer to any acoustic transducer intended to be mechanically held in place proximate to a user's ear canal and include, without limitation, earphones, earbuds, and other similar devices. As more specific examples, "earbuds" or "headphones" may refer to intra-concha earphones, supra-concha earphones and supra-aural earphones. Further, the techniques disclosed herein are applicable to other forms of acoustic noise canceling, and the term "transducer" includes headphone or speaker type transducers, but also other vibration generators such as piezo-electric transducers, magnetic vibrators such as motors, and the like. The term "sensor" includes microphones, but also includes vibration sensors such as piezo-electric films, and the like.

FIG. **2** shows a simplified schematic diagram of audio integrated circuits **20**A, **20**B that include ANC processing, as coupled to respective reference microphones R**1**, R**2**, which provides measurements of ambient audio sounds that are filtered by the ANC processing circuits within audio integrated circuits **20**A, **20**B, located within corresponding earbuds EB**1**, EB**2**. In purely feedback implementations, reference microphone R may be omitted and the anti-noise signal generated entirely from error microphones E**1**, E**2**. Audio integrated circuits **20**A, **20**B may be alternatively combined in a single integrated circuit, such as integrated circuit **20** within wireless telephone **10**. Further, while the connections shown in FIG. **2** apply to the wireless telephone system depicted in FIG. **1**B, the circuits disclosed in FIG. **2** are applicable to wireless telephone **10** of FIG. **1**A by omitting audio integrated circuit **20**B, so that a single reference microphone input is provided for each of reference microphone R and error microphone E and a single output is provided for speaker SPKR. Audio integrated circuits **20**A, **20**B generate outputs for their corresponding channels that are provided to the corresponding one of speakers SPKR**1**, SPKR**2**. Audio integrated circuits **20**A, **20**B receive the signals (wired or wireless depending on the particular configuration) from reference microphones R**1**, R**2**, near-speech microphone NS and error microphones E**1**, E**2**. Audio integrated circuits **20**A, **20**B also interface with other integrated circuits such as RF integrated circuit **12** containing the wireless telephone transceiver shown in FIG. **1**A. In other configurations, the circuits and techniques disclosed herein may be incorporated in a single integrated circuit that contains control circuits and other functionality for implementing the entirety of the personal audio device, such as an MP3 player-on-a-chip integrated circuit. Alternatively, multiple integrated circuits may be used, for example, when a wireless connection is provided from each of earbuds EB**1**, EB**2** to wireless telephone **10** and/or when some or all of the ANC processing is performed within earbuds EB**1**, EB**2** or a module disposed along a cable connecting wireless telephone **10** to earbuds EB**1**, EB**2**.

Audio integrated circuit **20**A includes an analog-to-digital converter (ADC) **21**A for receiving the reference microphone signal from reference microphone R**1** (or reference microphone R in FIG. **1**A) and generating a digital representation ref of the reference microphone signal. Audio integrated circuit **20**A also includes an ADC **21**B for receiving the error microphone signal from error microphone E**1** (or error microphone E in FIG. **1**A) and generating a digital representation err of the error microphone signal, and an ADC **21**C for receiving the near-speech microphone signal from near-speech microphone NS and generating a digital representation of near-speech microphone signal ns. (In the dual earbud system of FIG. **1**B, audio integrated circuit **20**B receives the digital representation of near-speech microphone signal ns from audio integrated circuit **20**A via the wireless or wired connections as described above.) Audio integrated circuit **20**A generates an output for driving speaker SPKR**1** from amplifier A**1**, which amplifies the output of a digital-to-analog converter (DAC) **23** that receives the output of a combiner **26**. Combiner **26** combines audio signals ia from internal audio sources **24**, and the anti-noise signal anti-noise generated by an ANC circuit **30**, which by convention has the same polarity as the noise in error microphone signal err and reference microphone signal ref and is therefore subtracted by combiner **26**. Combiner **26** also combines an attenuated portion of near-speech signal ns, i.e., sidetone information st, so that the user of wireless telephone **10** hears their own voice in proper relation to downlink speech ds, which is received from a radio frequency (RF) integrated circuit **22**. Near-speech signal ns is also provided to RF integrated circuit **22** and is transmitted as uplink speech to the service provider via an antenna ANT.

Referring now to FIG. **3**A, a simplified feedback ANC circuit is shown which applies in examples of the wireless telephone shown in FIG. **1**A, and to each channel of the wireless telephone system shown in FIG. **1**B. Ambient sounds Ambient travel along a primary path P(z) to error microphone E and are filtered by a feedback filter **38** to generate anti-noise provided through amplifier A**1** to speaker SPKR. Secondary path S(z) includes the electrical path from the output of feedback filter **38** to speaker SPKR combined with the acoustic path from the speaker SPKR through error microphone E to the input of feedback filter **38**. Secondary path S(z) and feedback filter **38** constitute a feedback loop with a feedback gain $G_{FB}(z)=1/(1+H(z)S(z))=Q(z)/(\text{Ambient}*P(z))$, where Q(z) is the error microphone signal. Q(z) is corrected, if needed, to remove any playback audio that is not the anti-noise signal. Thus, the feedback gain $G_{FB}(z)$, which determines the effectiveness of the acoustic noise canceling, is dependent on the response of secondary path S(z) and the transfer function H(z) of feedback filter **38**. Since $G_{FB}(z)$ varies with the response of secondary path S(z), an ANC feedback controller must generally be designed using multiple models representing extreme values of the response of secondary path S(z) and H(z) must be conservatively designed in order to maintain a proper phase margin (i.e., the phase between the ambient sounds and the anti-noise reproduced by speaker SPKR at an upper frequency bound at which the G(z) falls to unity) and gain margin (i.e., the attenuation relative to unity of the ambient sounds and the anti-noise reproduced by speaker SPKR at one or more frequencies for which the phase between the ambient sounds and the anti-noise reaches zero, causing positive feedback). A proper phase margin/gain margin are necessary for stability of the feedback loop in an ANC system employing feedback, as the phase margin/gain margin are directly determinative of the recovery of the ANC system from a disturbance, such as high-amplitude noise, or noise that the ANC system cannot cancel. On the other hand, increasing the gain and phase margins typically requires lowering the upper limit of the frequency response of the feedback loop, reducing the ability of the ANC system to cancel ambient noise. A wide variation in the response of secondary path S(z) constrains any off-line design of the feedback controller such that the performance of the feedback cancelation is limited at higher frequencies. A wide variation in the response of secondary path S(z) is typical for wireless telephones, earbuds, and the other devices described above, which are used in or in proximity to a user's ear canal.

Referring now to FIG. **3**B, a simplified feed-forward/feedback ANC circuit is shown which alternatively applies to the wireless telephone shown in FIG. **1**A, and to each channel of the wireless telephone system shown in FIG. **1**B. The operation of the feed-forward/feedback ANC is similar to the pure feedback approach shown in FIG. **3**A, except that the anti-noise signal provided to amplifier A**1** is generated by both the feedback filter **38** described above, and a feed-forward filter **32**, which generates a portion of the anti-noise signal from the output of reference microphone R. Combiner **36** combines the feed-forward anti-noise with the feedback anti-noise. The feedback gain of feedback filter **38** is still $G_{FB}(z)=1/(1+H(z)S(z))=Q(z)/(\text{Ambient}*P(z))$.

Referring now to FIGS. **4**A-**4**D, details of various exemplary ANC circuits **20** that may be included within audio integrated circuits **20**A, **20**B of FIG. **2**, are shown in accordance with various embodiments of the disclosure. In each of the examples, the above-described feedback filter **38** is implemented as a pair of filters. A first filter **40** has a fixed predetermined response that is related to and helps maintain stability of the compensated feedback loop and contributes to the ANC gain of the ANC system. The other filter is a variable-response filter **42**,**42**A that compensates for the variations of at least a portion of the response of secondary path S(z). The result is that the feedback ANC gain $G_{FB}(z)$ is rendered independent of the variations in the response of secondary path S(z). In the equation given above for feedback gain $G_{FB}(z)=1/(1+H(z)S(z))$ is equal to $1/(1+B(z)C(z)S(z))$. Thus when C(z) is set to the inverse $S^{-1}(z)$ of the response of secondary path S(z), $G_{FB}(z)=1/(1+B(z)S^{-1}(z)S(z))=1/(1+B(z)z^{-D})$ given $S^{-1}(z)\,S(z)=z^{-D}$, where z^{-D} is a delay include to provide a causal design for filter **42**A to model the inverse $S^{-1}(z)$ of the response of secondary path S(z). Thus, when $C(z)=S^{-1}(z)$, the variable transfer function of filter **42**, **42**A in the circuits of FIGS. **4**A-**4**D compensates for variation in the response of secondary path S(z). The feedback gain $G_{FB}(z)$ therefore becomes a uniform feedback gain $G_{FB,uniform}(z)$ that no longer depends upon the variable response of secondary path S(z). Uniform feedback gain $G_{FB,uniform}(z)$ then relates to or depends upon only a fixed transfer function B(z) and a set delay z^{-D} and fixed transfer function B(z) becomes the sole control variable in determining the ANC feedback control response. In each of the cascaded filter configurations shown in FIGS. **4**A-**4**D, the order of filter **40** and filters **42**, **42**A in the cascade may be interchanged.

FIG. **4**A shows an ANC feedback filter **38**A that receives the error microphone signal err from error microphone E, filters the error microphone signal with filter **42** having a response C(z), and filters the output of filter **42** with another filter **40** having a predetermined fixed response B(z). Response C(z) represents any filter response that helps stabilize the ANC system against variations in the response of secondary path S(z), and depending on other portions of the system response, may or may not be exactly equal to the inverse $S^{-1}(z)$ of the response of secondary path S(z). FIG. **4**B illustrates another ANC feedback filter **38**B in which first filter **42**A has a response $SE^{-1}(z)$ that is an estimate of the inverse $S^{-1}(z)$ of the response of secondary path S(z), and is controlled according to control signals from a secondary path estimator SE(z) control circuit. FIG. **4**C illustrates yet another ANC feedback filter **38**C in which first filter **42**B is an adaptive filter that estimates response $S^{-1}(z)$ to generate inverse response $SE^{-1}(z)$ via off-line calibration. When a switch S**1** is opened (and thus ANC operation is muted), a playback signal PB (that is also reproduced by the output transducer) with delay z^{-D} applied by delay **47** is correlated with error microphone signal err by a least-means-squared (LMS) coefficient controller **44**, after the output of first filter **42**B is subtracted from playback signal PB by a combiner **46**. The resulting adaptive filter obtains an estimate of the response of secondary path S(z) by directly measuring the effect of the response of secondary path S(z) on playback signal PB. When ANC circuit **38**C is operated on-line, switch S**1** is closed and the outputs of LMS coefficient controller **44** are held constant and converted to invert the response of adaptive filter **42**A to yield response $SE^{-1}(z)$. Adaptive filter **42**A operates as a fixed non-adaptive filter when on-line.

Referring to FIG. **4**D, a feed-forward/feedback implementation of the above-described control scheme is shown. Adaptive feed-forward filter **32** receives reference microphone signal ref and under ideal circumstances, adapts its transfer function W(z) to be some portion of P(z)/S(z) to generate the feed-forward anti-noise signal FF anti-noise, which is provided to output combiner **36** that combines feed-forward anti-noise signal FF anti-noise with a feedback anti-noise signal FB anti-noise generated by an ANC feedback filter **38**D. As described above, ANC feedback filter **38**D includes first filter **40** having fixed predetermined response B(z) and variable-response filter **42**A that receives control inputs that cause the response of filter **42**A to model inverse response $SE^{-1}(z)$. The coefficients of feed-forward adaptive filter **32** are controlled by a W coefficient control block **31** that uses a correlation of two signals to determine the response of adaptive filter **32**, which generally minimizes the error, in a least-mean squares sense, between those components of reference microphone signal ref present in error microphone signal err. The signals processed by W coefficient control block **31** are the reference microphone signal ref as shaped by a copy of an estimate of the response of path S(z) provided by a controllable filter **34**B and another signal that includes error microphone signal err. By transforming reference microphone signal ref with a copy of the estimate SE(z) of the response of secondary path S(z), response $SE_{COPY}(z)$, and minimizing error microphone signal err after removing components of error microphone signal err due to playback of source audio, i.e., playback corrected error signal PBCE, adaptive filter **32** adapts to the desired portion of the response of P(z)/S(z). To generate the estimate SE(z) of the response of secondary path S(z), ANC circuit **30** includes controllable filter **34**B having an SE coefficient control block **33** that provides control signals that set the response of adaptive filter **34**A and controllable filter **34**B to response SE(z). SE coefficient control block **33** also provides control signals to coefficient inversion block **37** that computes coefficients that set the response of variable response filter **42**A to inverse response $SE^{-1}(z)$ from the coefficients that determine response SE(z).

In addition to error microphone signal err, the other signal processed along with the output of controllable filter **34**B by W coefficient control block **31** includes an inverted amount of the source audio including downlink audio signal ds and internal audio ia that has been processed by filter response SE(z), of which response $SE_{COPY}(z)$ is a copy. By injecting an inverted amount of source audio, adaptive filter **32** is prevented from adapting to the relatively large amount of source audio present in error microphone signal err and by transforming the inverted copy of downlink audio signal ds and internal audio ia with the estimate of the response of path S(z). The source audio that is removed from error microphone signal err before processing should match the expected version of downlink audio signal ds, and internal audio ia reproduced at error microphone signal err, since the electrical and acoustical path of S(z) is the path taken by downlink audio signal ds and internal audio ia to arrive at error microphone E. Filter **34**B is not an adaptive filter, per se, but has an adjustable response that is tuned to match the response of adaptive filter **34**A, so that the response of controllable filter **34**B tracks the adapting of adaptive filter **34**A.

Adaptive filter **34**A and SE coefficient control block **33** process the source audio (ds+ia) and error microphone signal err after removal, by combiner **36**, of the above-described filtered downlink audio signal ds and internal audio ia, that has been filtered by adaptive filter **34**A to represent the expected source audio delivered to error microphone E. The output of combiner **36** is further filtered by an alignment filter **35** having response $1+B(z)z^{-D}$ to remove the effects of the feedback signal path on the source audio delivered to error microphone E. Alignment filter **35** is described in further detail in U.S. patent application Ser. No. 14/832,585 filed on Aug. 21, 2015 entitled "HYBRID ADAPTIVE NOISE CANCELLATION SYSTEM WITH FILTERED ERROR MICROPHONE SIGNAL", the disclosure of which is incorporated herein by reference. In the above-incorporated patent application, an alignment filter is used having variable response 1+SE(z)H(z) to remove the effect of the feedback portion of the ANC system, including the secondary path, on the error signal, but since in the instant disclosure $H(z)=B(z)SE^{-1}(z)$, alignment filter **35** has response $1+SE(z)H(z)=1+SE(z)SE^{-1}(z)B(z)=1+B(z)z^{-D}$. Adaptive filter **34**A is thereby adapted to generate a signal from downlink audio signal ds and internal audio ia, that when subtracted from error microphone signal err, contains the content of error microphone signal err that is not due to source audio (ds+ia).

Referring now to FIGS. **5**A-**5**F, graphs of amplitude and phase responses of portions of the ANC systems described above are shown. FIG. **5**A shows an amplitude response (top) and phase response (bottom) of secondary path S(z) for various users. As can be seen from the graph, the variation in the amplitude of the response of secondary path S(z) varies by 10 dB or more in frequency regions of interest (typically 200 Hz to 3 KHz). FIG. **5**B shows a possible design amplitude response (top) and phase response (bottom) of filter **40** response B(z), while FIG. **5**C shows the response of $SE(z)SE^{-1}(z)$ for a simulated ANC system in accordance with the above disclosure. FIG. **5**D shows a convolution of $SE(z)SE^{-1}(z)$, illustrating that the resulting response is a short delay, e.g., 3 taps of filter **42**, **42**A. FIG. **5**E shows the response B(z)C(z) of the adaptive controller in the simulated system, and FIG. **5**F shows the closed-loop response of the simulated system, showing that the gain variation for all users has been reduced to about 2 dB across the entire illustrated frequency range.

Referring now to FIG. **6**, a filter circuit **40**A that may be used to implement fixed filter **40** is shown. The input signal is weighted by coefficients a_1, a_2 and a_3 by corresponding multipliers **55**A, **55**B and **55**C and provided to respective combiners **56**A, **56**B, **56**C at feed-forward taps of the filter stages, which comprise digital integrators **50**A and **50**B. A feedback tap is provided by a delay **53** and a multiplier **55**D, providing the second-order low-pass response illustrated in FIG. **5**A. The resulting topology is a delta-sigma type filter. Depending on requirements of the ANC system, the response of fixed filter **40** may be a low-pass response, or a band-pass response.

Referring now to FIG. **7**, an alternative filter circuit **40**B that may be used to implement fixed filter **40** is shown. The input signal is weighted by coefficient a_0 by multiplier **65**C and added to the output signal by combiner **66**B to provide a feed-forward tap and the output of a first delay **62**A is weighted by coefficient a_0 by another multiplier **65**D and also combined with the output signal by combiner **66**B. A second delay **62**B provides a third input to combiner **66**B. The input signal is combined with feedback signals provided from the output of first delay **62**A and weighted by coefficient b_1 by a multiplier **65**A and from the output of second delay **62**B and weighted by coefficient b_2 by a multiplier **65**B. The resulting filter is a bi-quad that can be used to implement a low-pass or band-pass filter as described above.

Referring now to FIG. **8**, a block diagram of an ANC system is shown for implementing ANC techniques as described above and having a processing circuit **140** as may be implemented within audio integrated circuits **20**A, **20**B of FIG. **2**, which is illustrated as combined within one circuit, but could be implemented as two or more processing circuits that inter-communicate. A processing circuit **140** includes a processor core **102** coupled to a memory **104** in which are stored program instructions comprising a computer program product that may implement some or all of the above-described ANC techniques, as well as other signal processing. Optionally, a dedicated digital signal processing (DSP) logic **106** may be provided to implement a portion of, or alternatively all of, the ANC signal processing provided by processing circuit **140**. Processing circuit **140** also includes ADCs **21**A-**21**E, for receiving inputs from reference microphone R**1** (or error microphone R), error microphone E**1** (or error microphone E), near speech microphone NS, reference microphone R**2**, and error microphone E**2**, respectively. In alternative embodiments in which one or more of reference microphone R**1**, error microphone E**1**, near speech microphone NS, reference microphone R**2**, and error microphone E**2** have digital outputs or are communicated as digital signals from remote ADCs, the corresponding ones of ADCs **21**A-**21**E are omitted and the digital microphone signal(s) are interfaced directly to processing circuit **140**. A DAC **23**A and amplifier A**1** are also provided by processing circuit **140** for providing the speaker output signal to speaker SPKR**1**, including anti-noise as described above. Similarly, a DAC **23**B and amplifier A**2** provide another speaker output signal to speaker SPKR**2**. The speaker output signals may be digital output signals for provision to modules that reproduce the digital output signals acoustically.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made therein without departing from the spirit and scope of the invention.

What is claimed is:

1. An adaptive noise cancellation (ANC) controller, comprising:

a fixed filter having a predetermined fixed transfer function (B(z)) that relates to and maintains stability of a compensated feedback loop, wherein the fixed filter contributes to an ANC gain of an ANC system; and

a variable-response filter coupled to the fixed filter, wherein a response of the variable-response filter compensates for variations of a transfer function of a secondary path that includes at least a path from a transducer of the ANC system to a sensor of the ANC system, so that the ANC gain is independent of the variations in the transfer function of the secondary path, wherein the response of the variable-response filter is an inverse of the transfer function of the secondary path.

2. The ANC controller of claim **1**, wherein the fixed filter causes the ANC gain to be a uniform feedback gain that depends on the predetermined fixed transfer function.

3. The ANC controller of claim **1**, wherein the response of the variable response filter is controlled in conformity with a control output of an adaptive filter of the ANC system.

4. The ANC controller according to claim **3**, wherein the variable-response filter is the adaptive filter, whereby the response of the variable-response filter is dependent on frequency content of a signal provided as an input to the variable response filter to which the response of the variable-response filter is applied.

5. The ANC controller according to claim **3**, wherein the adaptive filter is an adaptive filter of a feed-forward portion of the ANC system that adapts to cancel the effects of the secondary path on a component of a signal reproduced by the transducer of the ANC system.

6. The ANC controller according to claim **1**, wherein the sensor is a microphone and the transducer is a speaker.

7. An integrated circuit (IC) for implementing at least a portion of an audio device including acoustic noise canceling, the integrated circuit comprising:

an output for providing an output signal to an output transducer including an anti-noise signal for countering the effects of ambient audio sounds in an acoustic output of the transducer;

at least one microphone input for receiving at least one microphone signal indicative of the ambient audio sounds and that contains a component due to the acoustic output of the transducer; and

a processing circuit that adaptively generates the anti-noise signal to reduce the presence of the ambient audio sounds heard by the listener, wherein the processing circuit implements a feedback filter having a response that generates at least a portion of the anti-noise signal from the at least one microphone signal, the feedback filter comprising a fixed filter having a predetermined fixed transfer function (B(z)) and a variable-response filter coupled to the fixed filter, wherein a response of the variable-response filter compensates for variations of a transfer function of a secondary path that includes at least a path from the transducer to the at least one microphone, wherein the response of the variable-response filter is an inverse of the transfer function of the secondary path.

8. The integrated circuit of claim **7**, wherein the fixed filter causes an ANC gain of the system formed by the feedback filter, the transducer, the at least one microphone and the secondary path to be a uniform feedback gain that depends on the predetermined fixed transfer function.

9. The integrated circuit of claim **7**, wherein the response of the variable response filter is controlled in conformity with a control output of an adaptive filter implemented by the processing circuit that models the secondary path.

10. The integrated circuit of claim **9**, wherein the variable-response filter is the adaptive filter, whereby the response of the variable-response filter is dependent on frequency content of a signal provided as an input to the variable response filter to which the response of the variable-response filter is applied.

11. The integrated circuit of claim **9**, wherein the processing circuit further implements a feed-forward adaptive filter that generates another portion of the anti-noise signal, and further implements a secondary path adaptive filter that adapts to cancel the effects of the secondary path on a component of a source audio signal reproduced by the transducer of the ANC system.

12. A method of canceling effects of ambient noise, the method comprising:

adaptively generating an anti-noise signal to reduce the presence of the ambient noise;

providing the anti-noise signal to a transducer;

measuring the ambient noise with a sensor of an ANC system; and

filtering an output of the sensor with a fixed filter having a predetermined fixed transfer function (B(z)) that relates to and maintains stability of a compensated feedback loop, wherein the fixed filter contributes to an ANC gain of the ANC system and a variable-response filter coupled to the fixed filter, wherein a response of the variable-response filter compensates for variations of a transfer function of a secondary path that includes at least a path from a transducer of the ANC system to the sensor, so that the ANC gain is independent of the variations in the transfer function of the secondary path, wherein the response of the variable-response filter is an inverse of the transfer function of the secondary path.

13. The method of claim **12**, wherein the filtering causes the ANC gain to be a uniform feedback gain that depends on the predetermined fixed transfer function.

14. The method of claim **12**, further comprising controlling the response of the variable response filter in conformity with a control output of an adaptive filter of the ANC system.

15. The method of claim **14**, wherein the variable-response filter is the adaptive filter, wherein the response of the variable-response filter controlled in dependence on frequency content of a signal provided as an input to the variable response filter to which the response of the variable-response filter is applied.

16. The method of claim **14**, wherein the adaptive filter is an adaptive filter of a feed-forward portion of the ANC system that adapts to cancel the effects of the secondary path on a component of a signal reproduced by the transducer of the ANC system.

17. The method of claim **12**, wherein the sensor is a microphone and the transducer is a speaker.

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